Fundamentals of Global Climate Change Science

Erik Ramberg

- Temperature of the Earth
- Radiative balance in the atmosphere
- Forcings and the Ice Ages
- Direct measurements of the surface temperature
- Ice sheet melting
- Ocean sea level rise and acidification
- Predictions for the future

Radiative Balance on Earth

So – what temperature do we predict the Earth to have?

Use Stefan-Boltzmann equation to relate incoming power from the Sun to the temperature of the Earth:

$$J(1-a) = \varepsilon\sigma T^4$$

Where J is the incoming power per area from the Sun, a is the albedo of the Earth (or what fraction of the incoming power is simply reflected), ε is the 'emissivity' of the Earth (or how radiant it is compared to a blackbody), σ is the Boltzmann constant, and T is the temperature of the Earth.

Plug in the numbers:

Average solar insolation at the Earth's surface is J=341 W/m^2 (seasonally +/- 3.5%)

Boltzmann constant is 5.67×10^{-8} $W/(m)^2(K)^4$

Albedo is about 30%

If Earth is a perfect blackbody, with $\varepsilon = 1$, then:

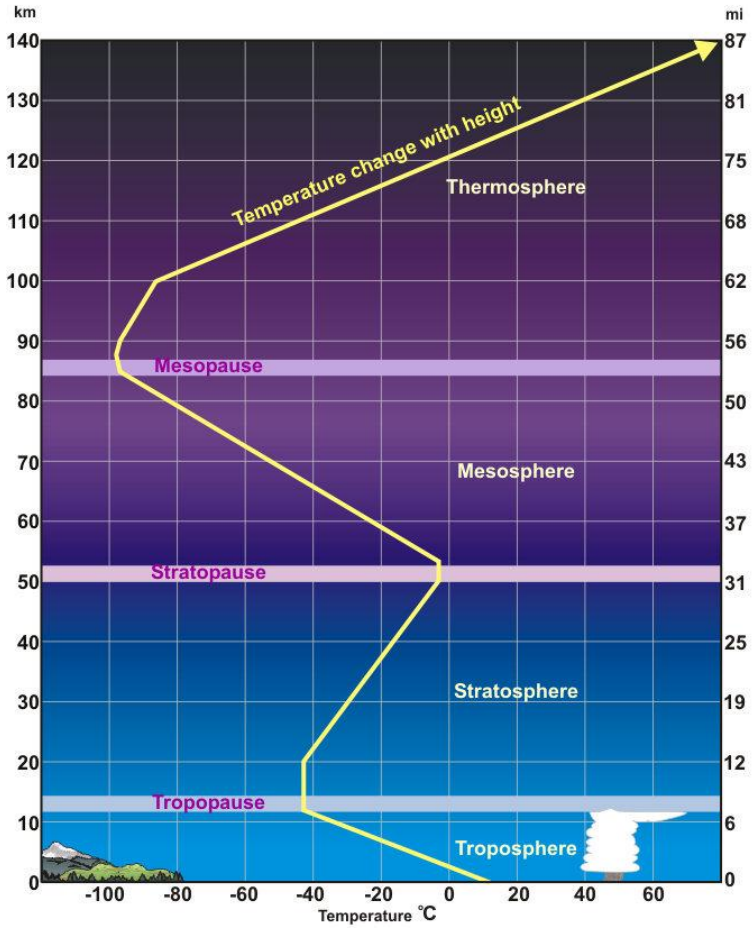
Predicted T = 255° K, or 0°F

Actual T = 289° K, or 60° F

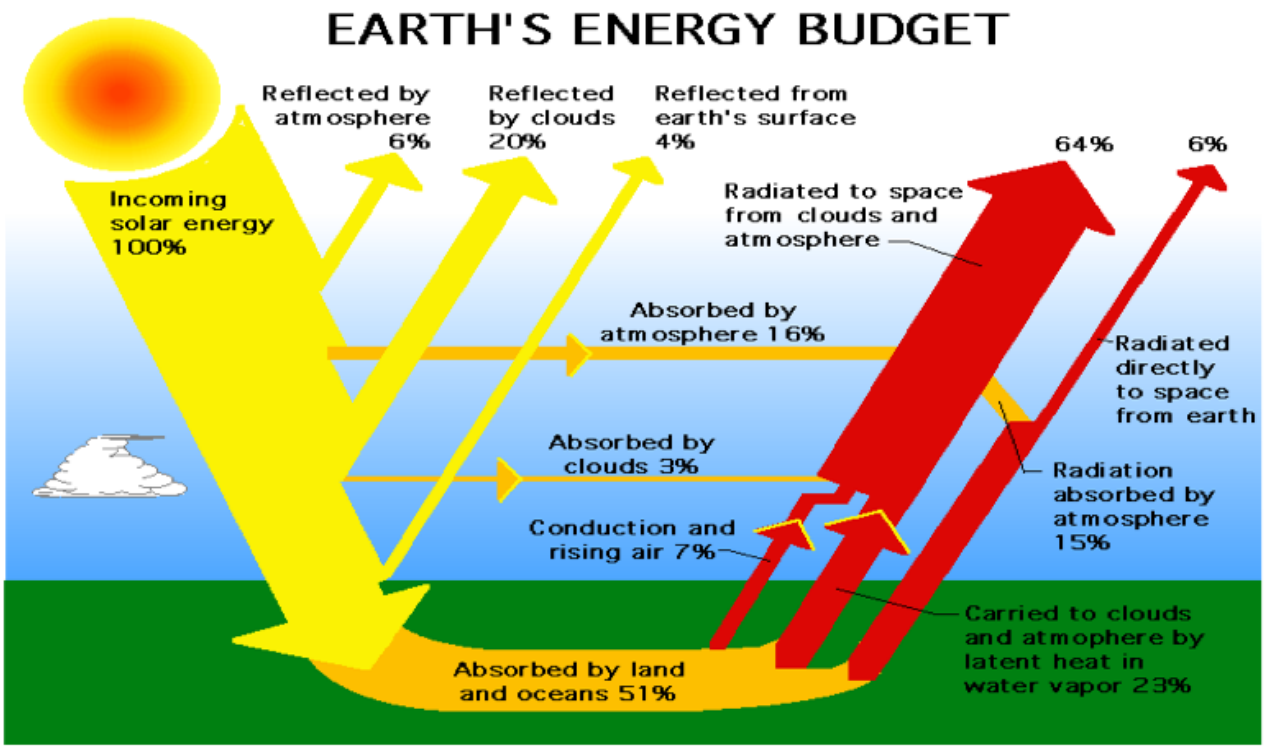
Difference must be due to details of emissivity of Earth

No True ‘Temperature’ !

- There is no true ‘temperature of the Earth’ because there is an atmosphere.
- You can talk about the temperature at the surface, or at some height from the surface
- The emissivity of the Earth depends on the composition of the gases in its atmosphere, their spectral properties and their distribution.
- The ocean plays a big role as well, as we shall see, but the time scale is much longer.



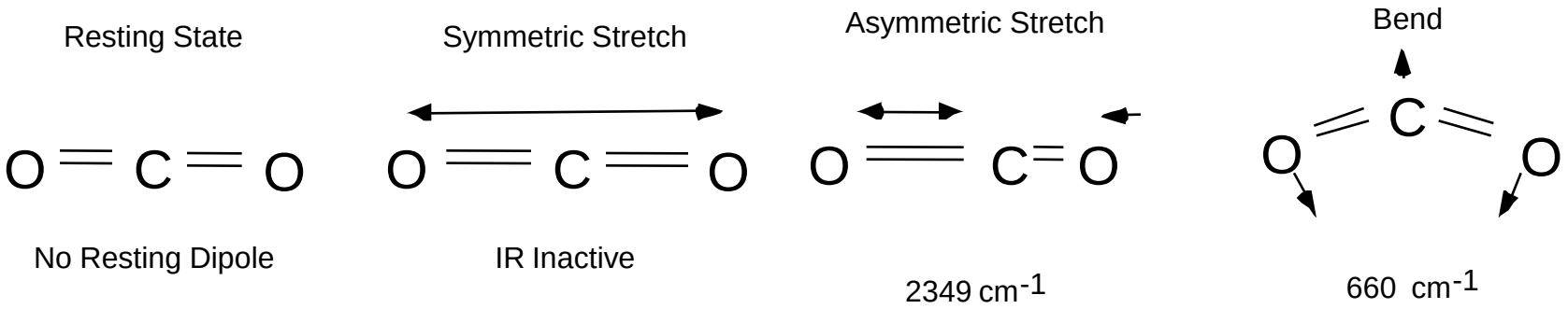
Radiation flow in the Earth system



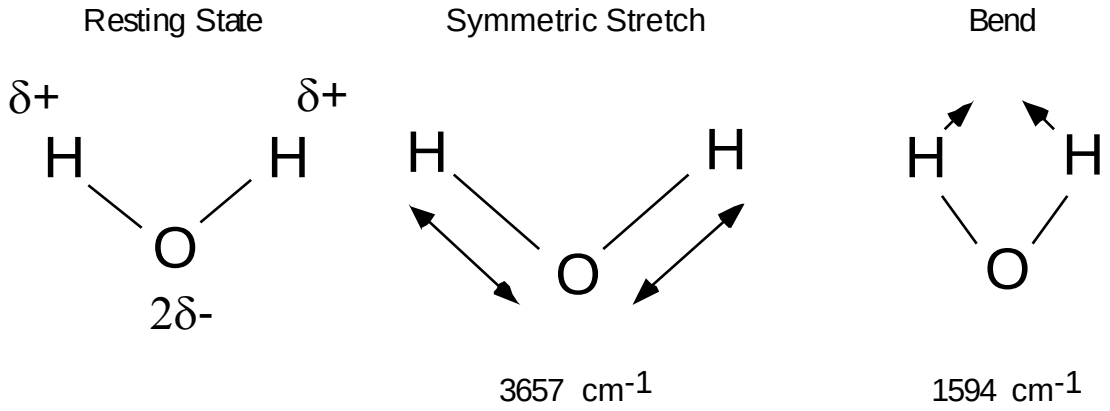
Top-of-the-Atmosphere radiation balance, or “TOA”, can be readily calculated using these flows between the various layers of the atmosphere, without worrying about the topographical details of the surface. These calculations inform us of average behavior.

More general climate models use the intricacies of the Earth’s surface, including winds, cloud formation and interaction with the ocean, to predict what the globe will look like in the future.

CO_2 absorption lines

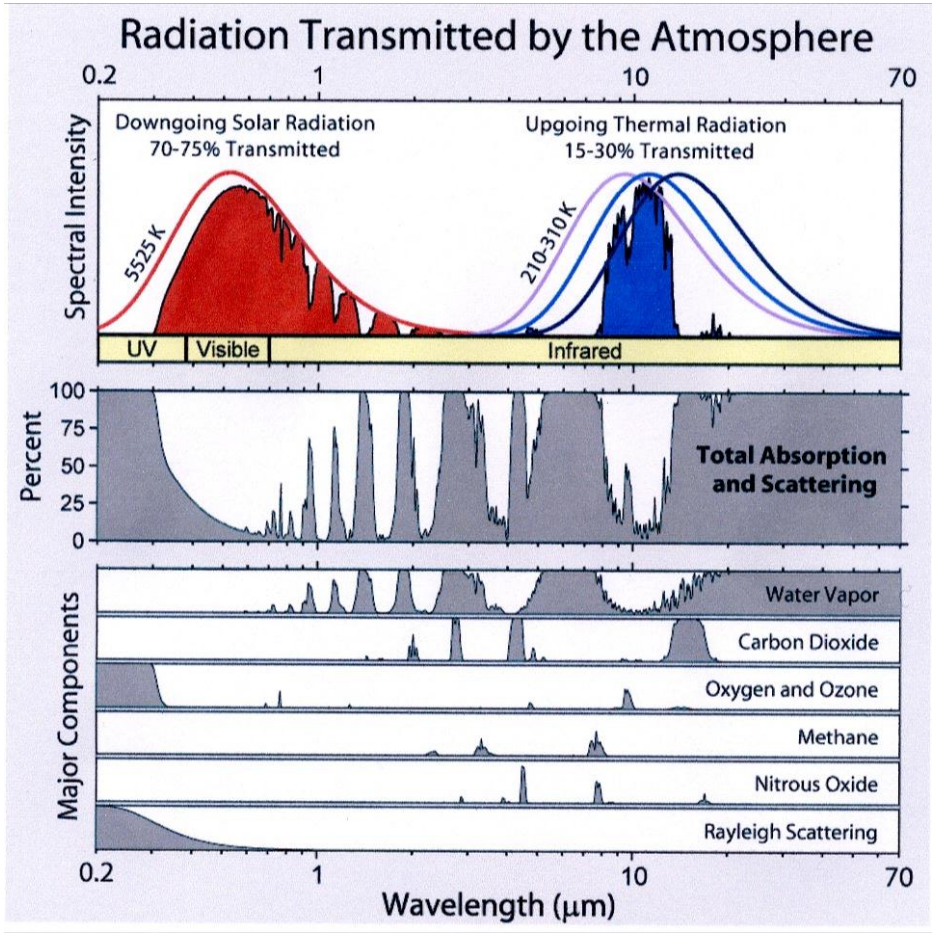


H_20 absorption lines



Infrared radiation from the Earth's surface will be absorbed by exciting these vibrations.

Absorption and Emission of Radiation on Earth



CO_2 and water absorb in the infrared region of 8-50 microns, which is the dominant wavelengths for a blackbody Earth.

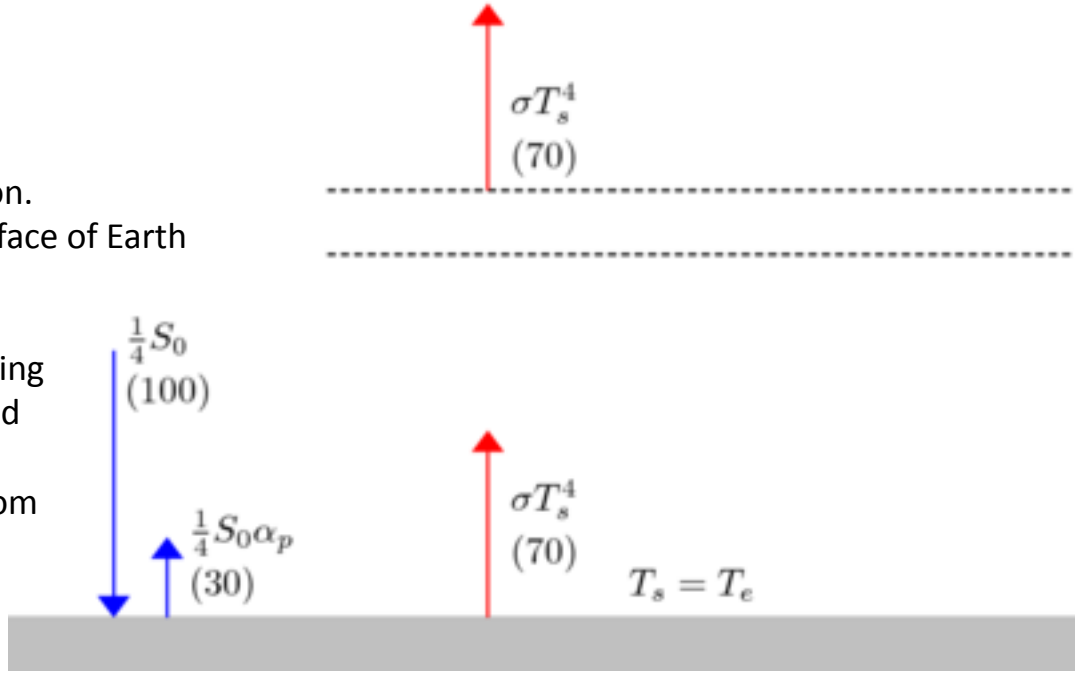
This is the 'Greenhouse effect', which has been understood for more than 100 years.

Note how powerful water is as a greenhouse gas.

The main difference between H_2O and CO_2 is that the lifetime of water in the atmosphere is weeks, while the lifetime of CO_2 in the atmosphere is on the order of 1000 years.

Idealized Greenhouse Model – No Atmospheric GHG

S_0 is total solar insolation.
¼ S_0 is average over surface of Earth

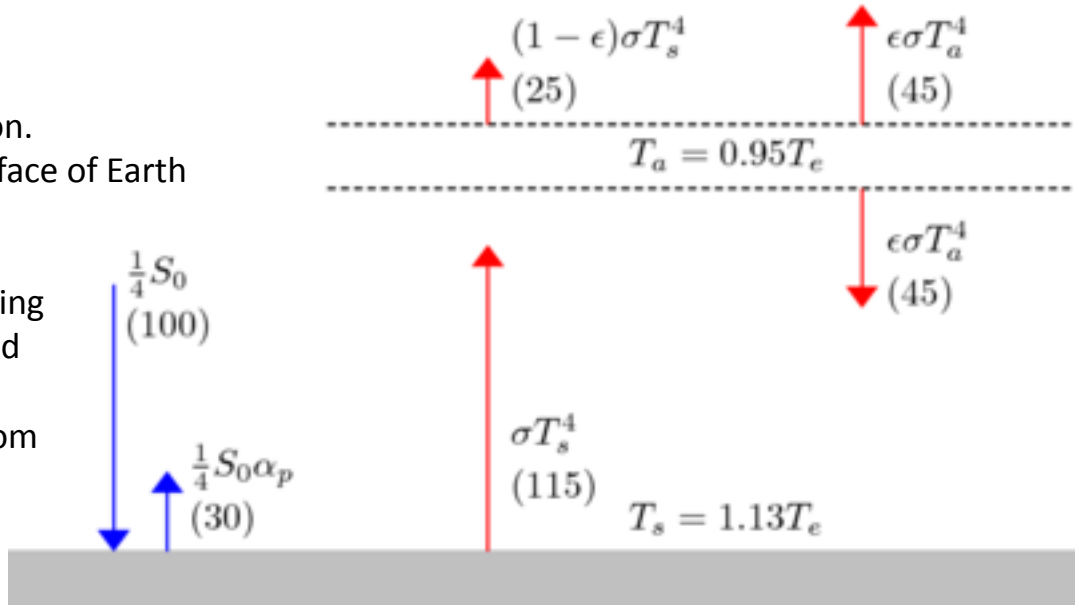


Blue: Incoming and reflected shortwave radiation from the sun

Red: outgoing longwave radiation.

Idealized Greenhouse Model – With Nominal GHG

S_0 is total solar insolation.
¼ S_0 is average over surface of Earth



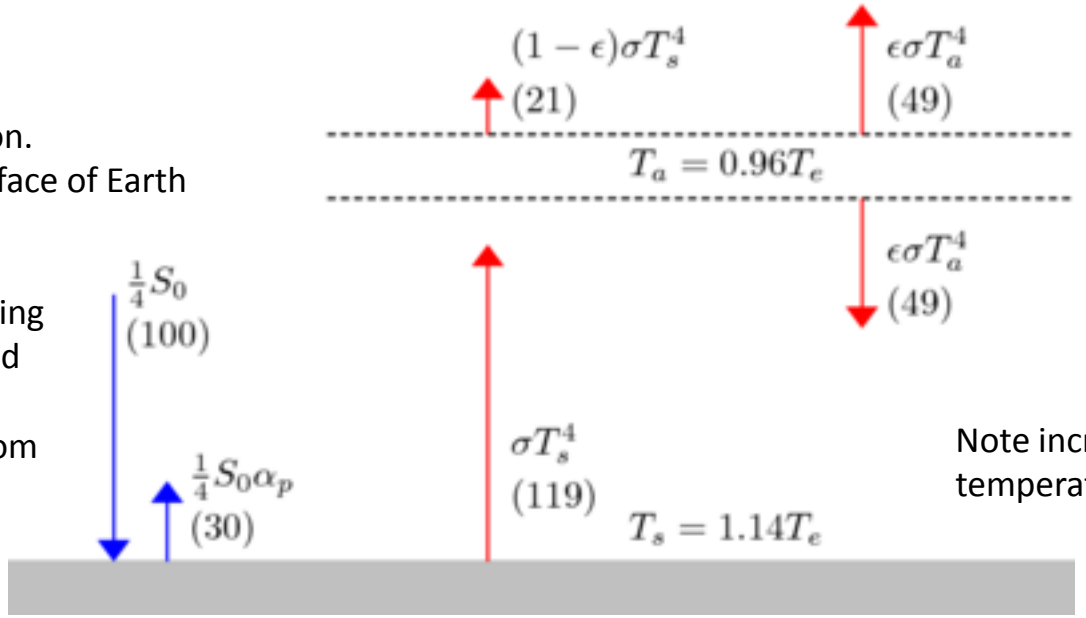
Note heating of surface and cooling of upper atmosphere

Blue: Incoming and reflected shortwave radiation from the sun

Red: outgoing longwave radiation.

Idealized Greenhouse Model – Doubling of CO2

S_0 is total solar insolation.
¼ S_0 is average over surface of Earth



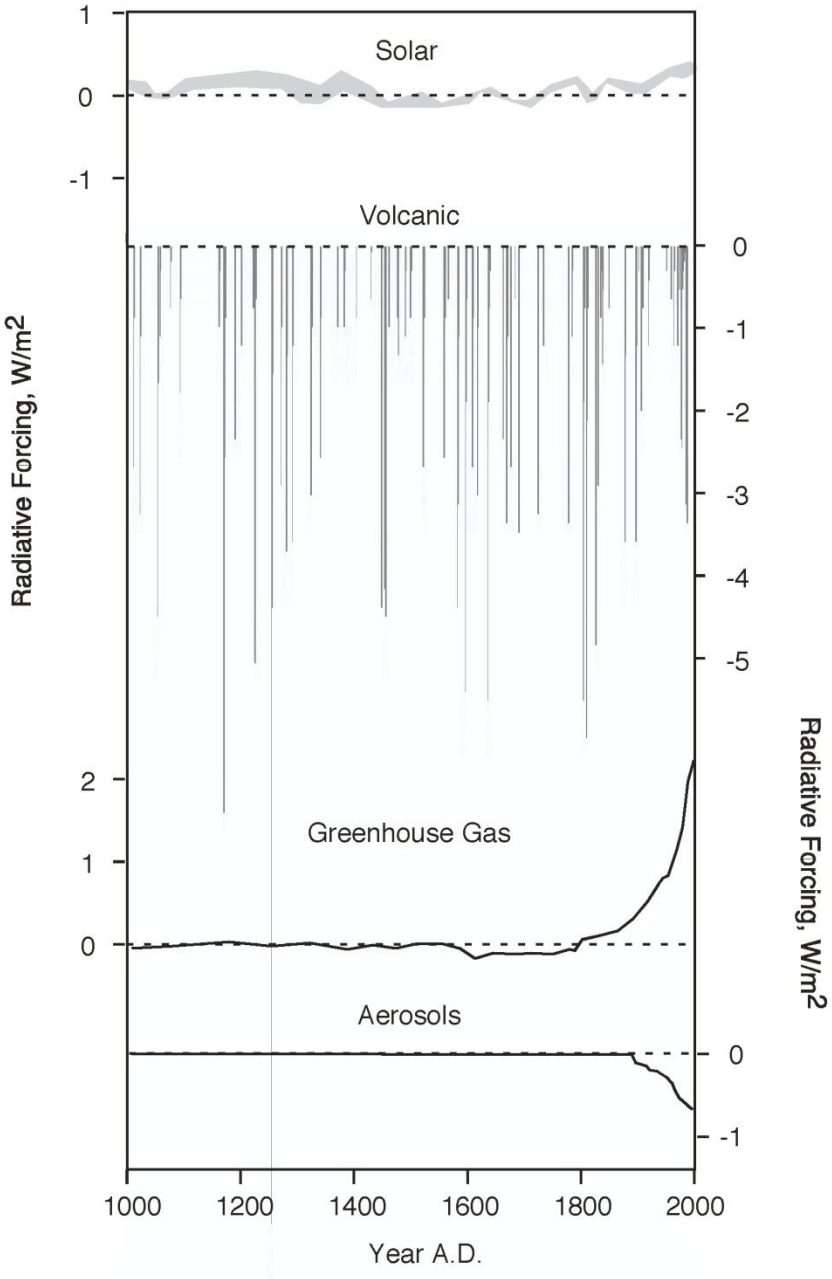
Note heating of surface and cooling of upper atmosphere

Blue: Incoming and reflected shortwave radiation from the sun

Note increase in surface temperature of <1%

Red: outgoing longwave radiation.

Forcings



Scale of Climate Forcings

'Forcing' = imbalance in radiative equilibrium

Solar variations are small

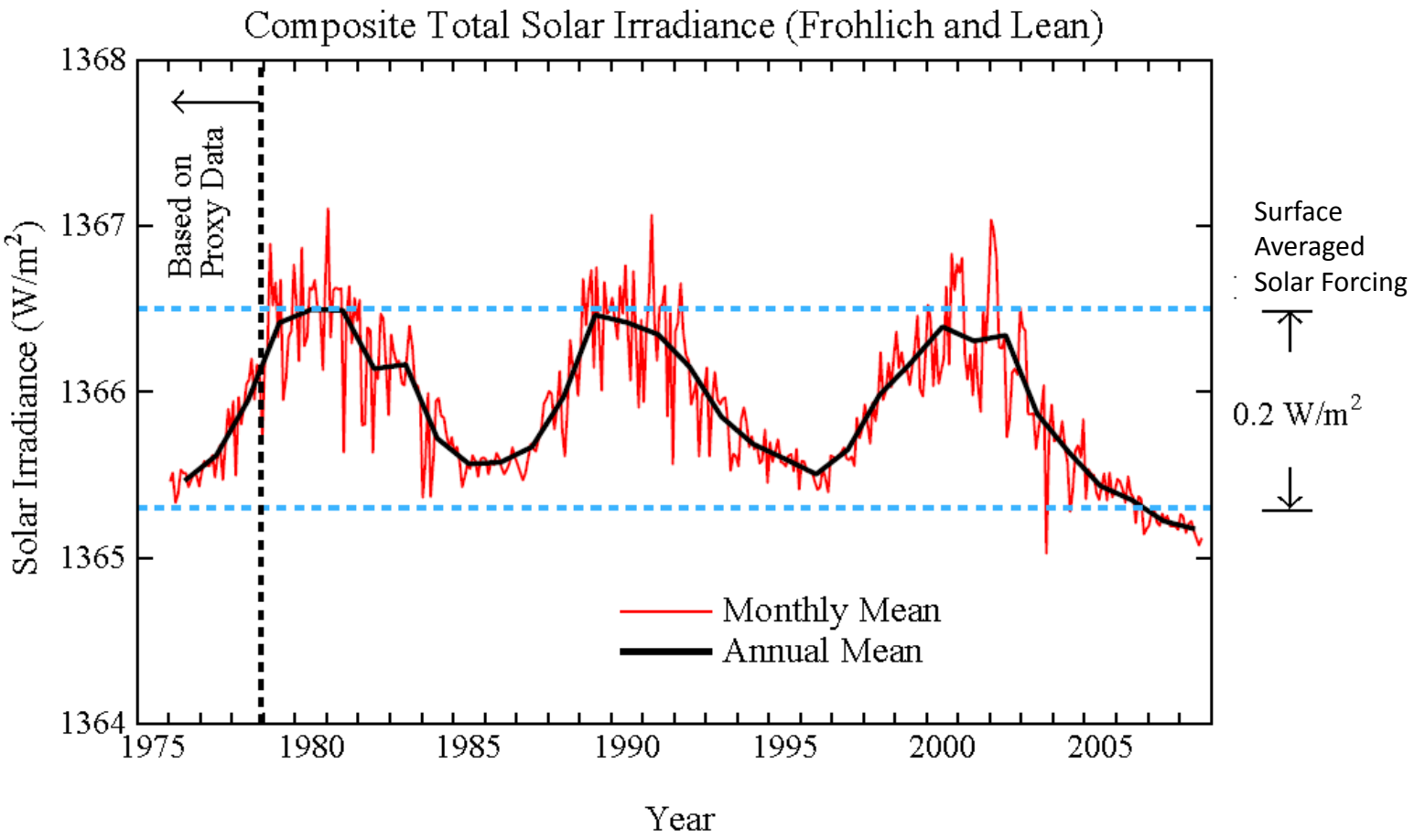
Volcanic aerosols block sunlight for short periods of time – average forcing is low

Man-made aerosols are more systemic and have to be taken into account

Only greenhouse gas forcing looks like the recent temperature rise.

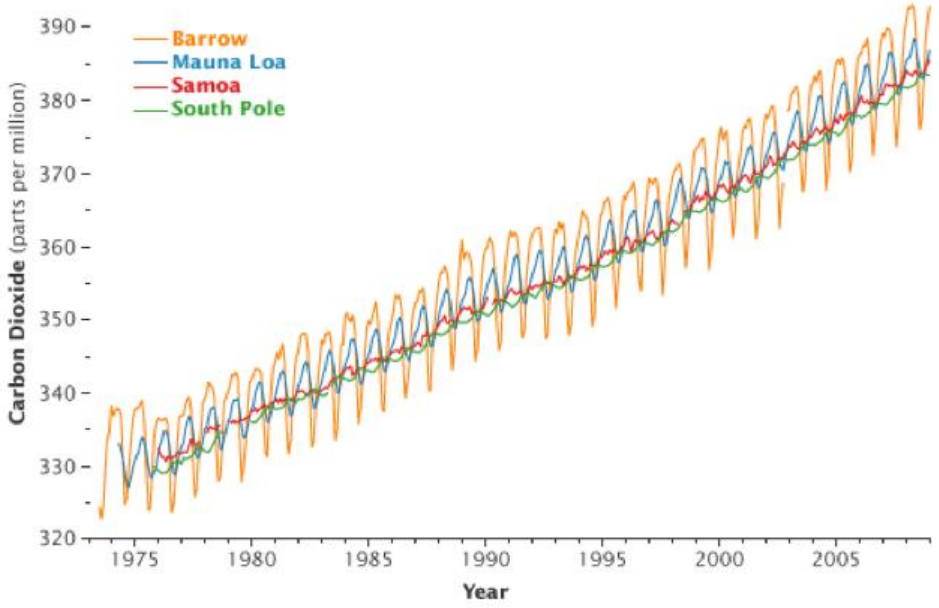
Crowley, 2000

Variations in Solar Output on the Short Time Scale are Irrelevant



Reference: Fröhlich, C. and J. Lean, *Astron. Astrophys. Rev.*, **12**, pp. 273--320, 2004.
http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant

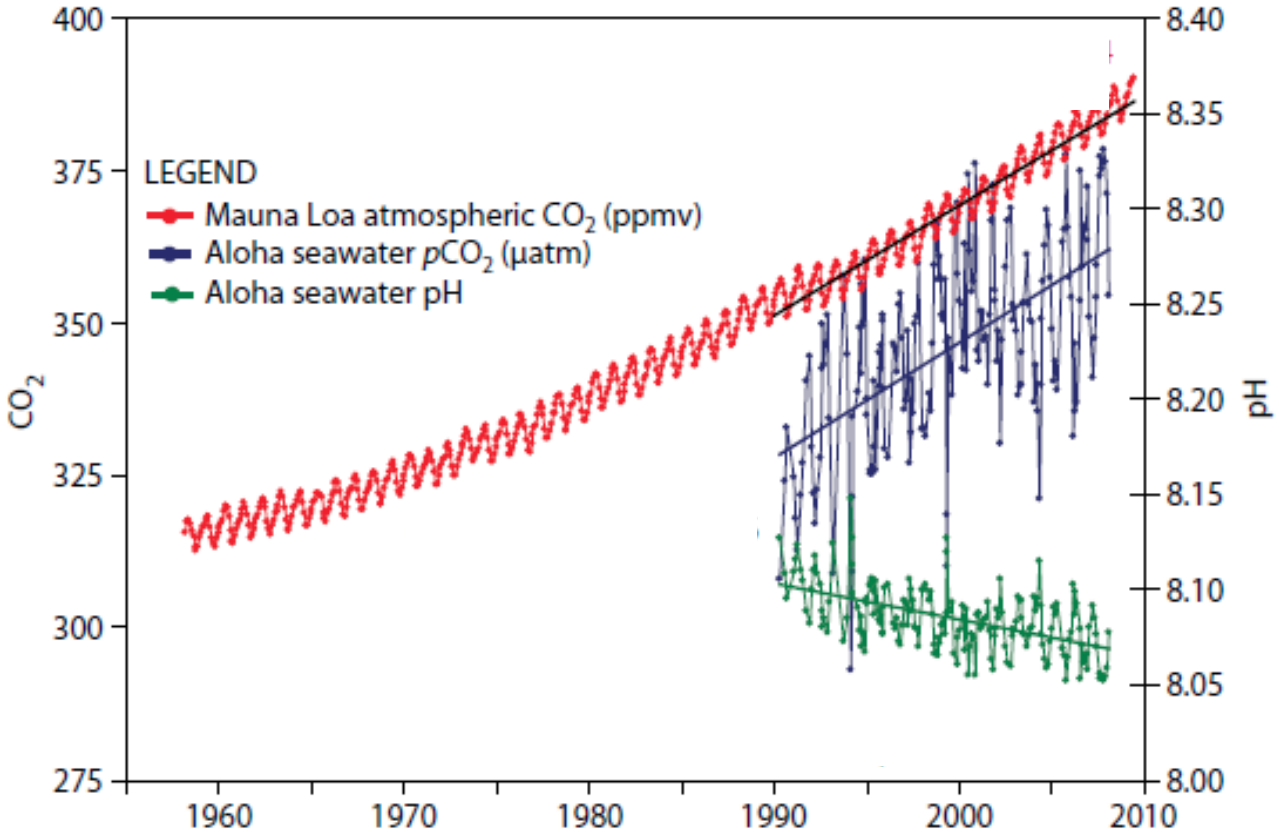
CO2 in the Atmosphere



The 'Keeling curve'

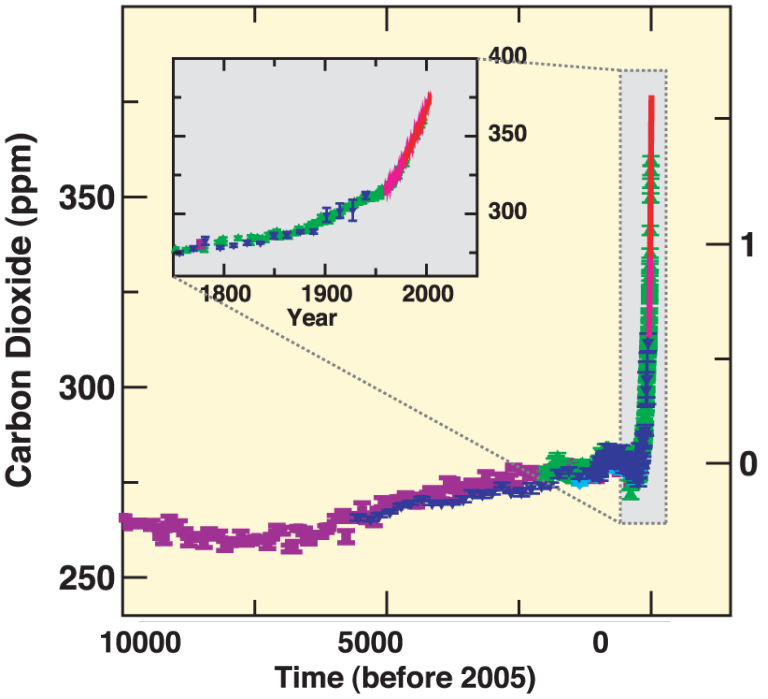
- Mankind's use of fossil fuel is causing the CO_2 concentration in the atmosphere to rise significantly.
- Measurements of carbon isotopes confirm that the new CO_2 is deficient in Carbon-14 and is thus buried carbon being released.
- This increase is about half the amount of CO_2 that is calculated as being put into the atmosphere from industrial processes.
- Where is the other half?

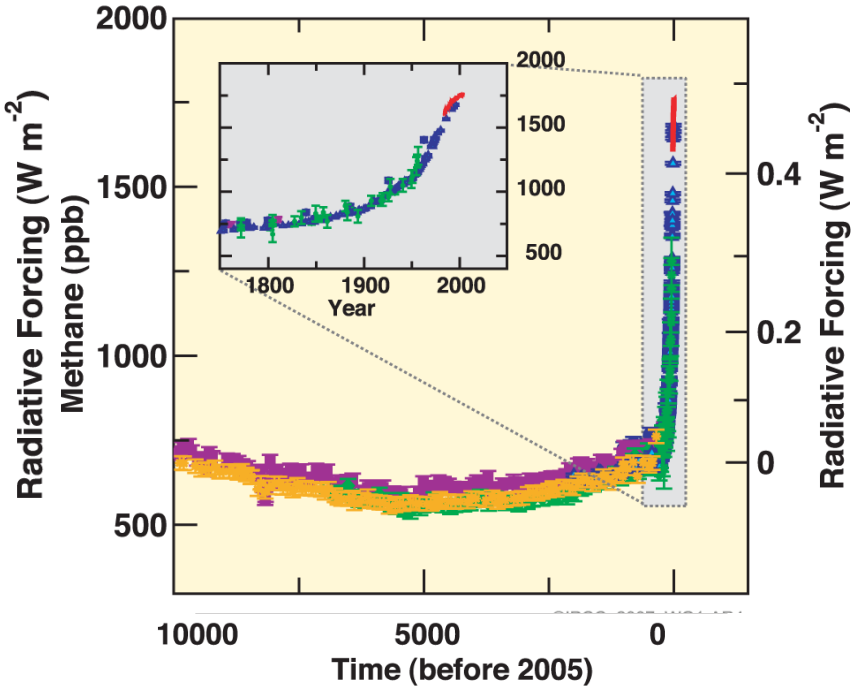
CO2 in the Ocean



- As shown by measuring the partial pressure of CO_2 in seawater, the ocean is absorbing about half of the industrial production of CO_2.
- The pH of the ocean is decreasing as a consequence. This acidification of the ocean is global in nature.

CO_2 and other GHG's are now the dominant elements of climate forcing, and it is instantaneous on geological time scales





CO_2

Methane

Source: IPCC AR4

Carbon cycle in the Earth/Atmosphere

- Note that the carbon resident in fossil fuels outweighs combined mass of carbon in atmosphere + soil + biomass + upper ocean
- Our impact on the atmosphere is about 0.7% per year, and rising

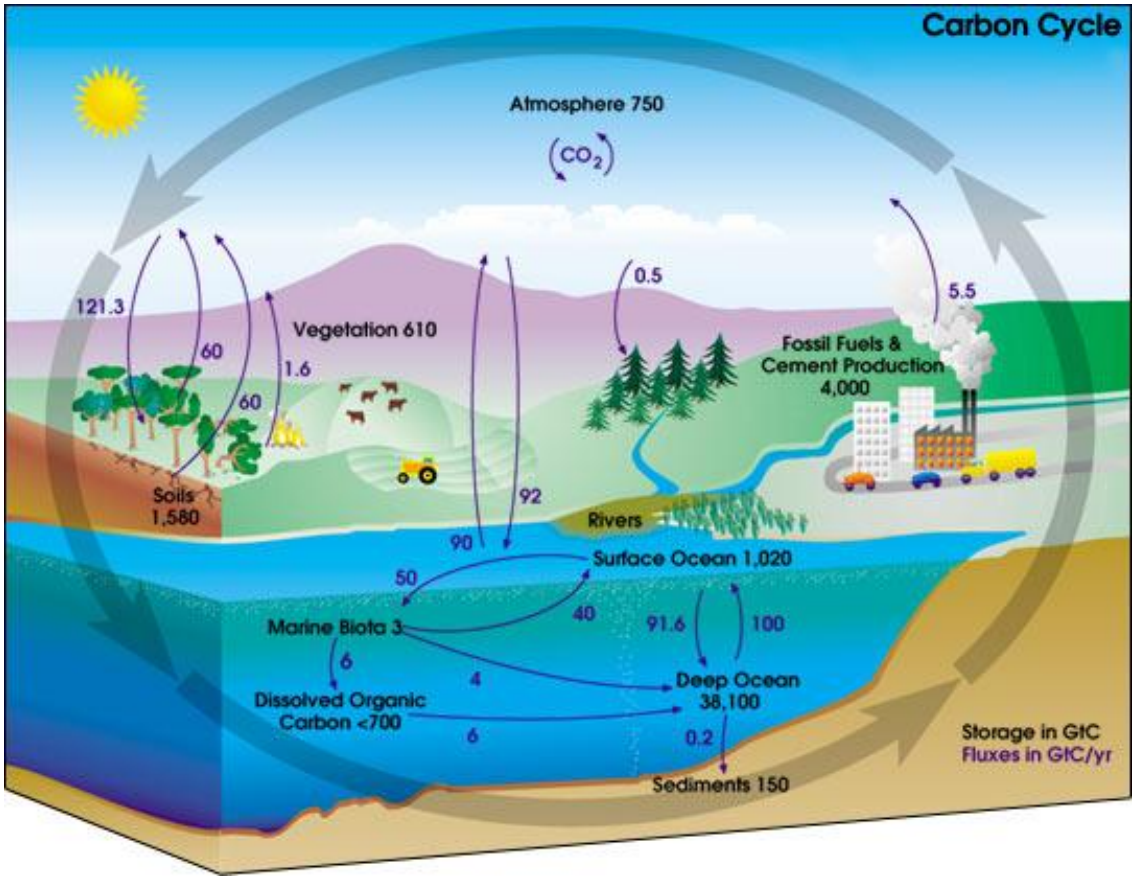


Illustration courtesy NASA Earth Science Enterprise.

Dependence of Temperature on Forcings, with No Feedbacks

Stefan Boltzmann:

$$F=J(1-a) = \varepsilon\sigma T^4, \text{ or } T = (J(1-a)/\varepsilon\sigma)^{1/4}$$

Derivative w/r Temperature:

$$dT/dF = (1/4)(1/\varepsilon\sigma)^{1/4}(F)^{-3/4}$$

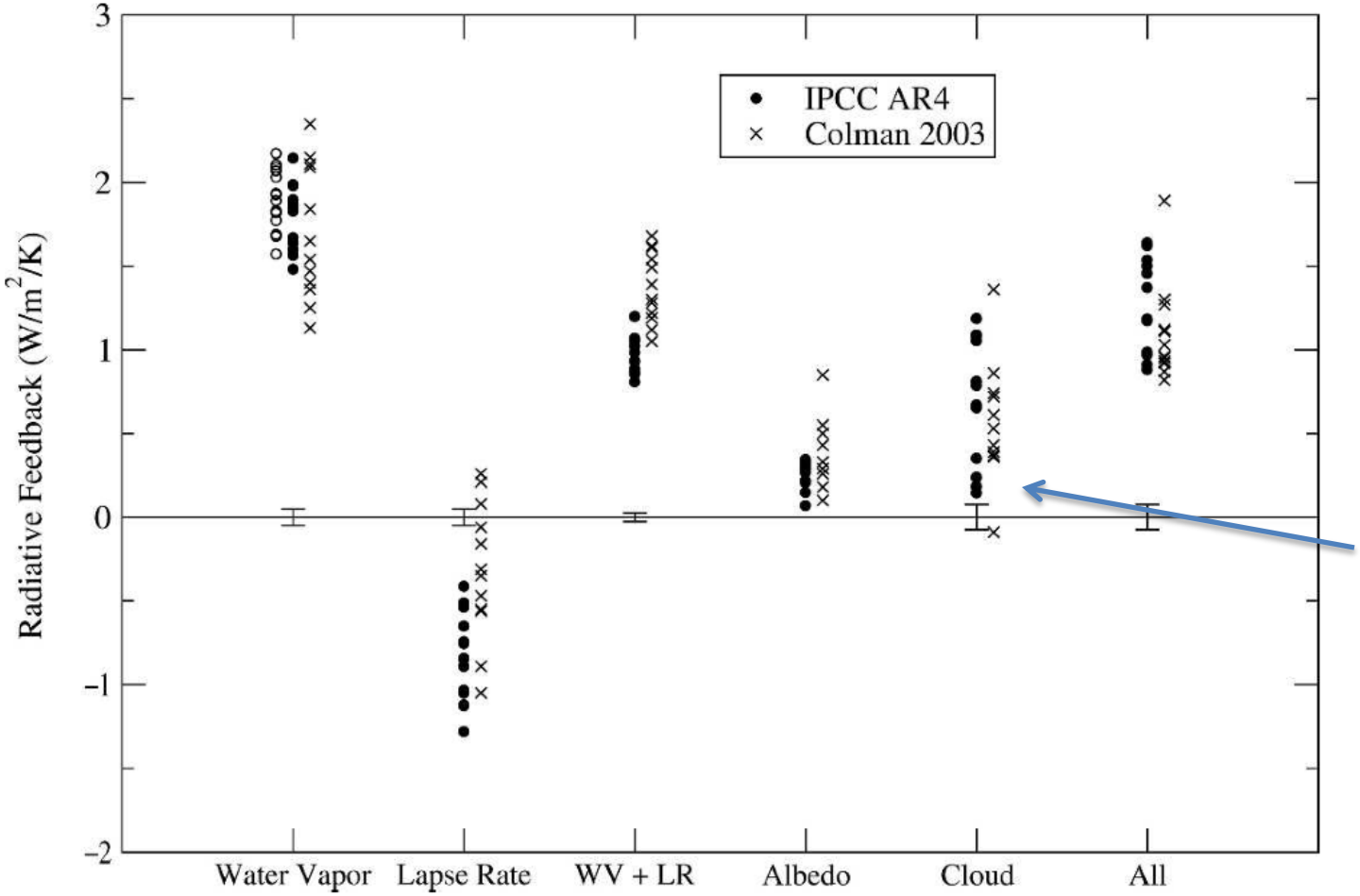
Assume $\varepsilon = 1$
Average solar insolation: J = 341 W/m^2
Boltzmann constant: $\sigma = 5.67 \times 10^{-8}$ W/(m)^2(K)^4
Albedo = 0.3

So, 'sensitivity' is:

$$dT = 0.3^oK \text{ per } 1 \text{ W/m}^2$$

As we will see, the measured effective 'sensitivity' on Earth is more like 0.8^o C per 1 W/m^2. The difference is due to water vapor, which is a powerful greenhouse gas, but is considered a feedback, since it falls out of the atmosphere so readily.

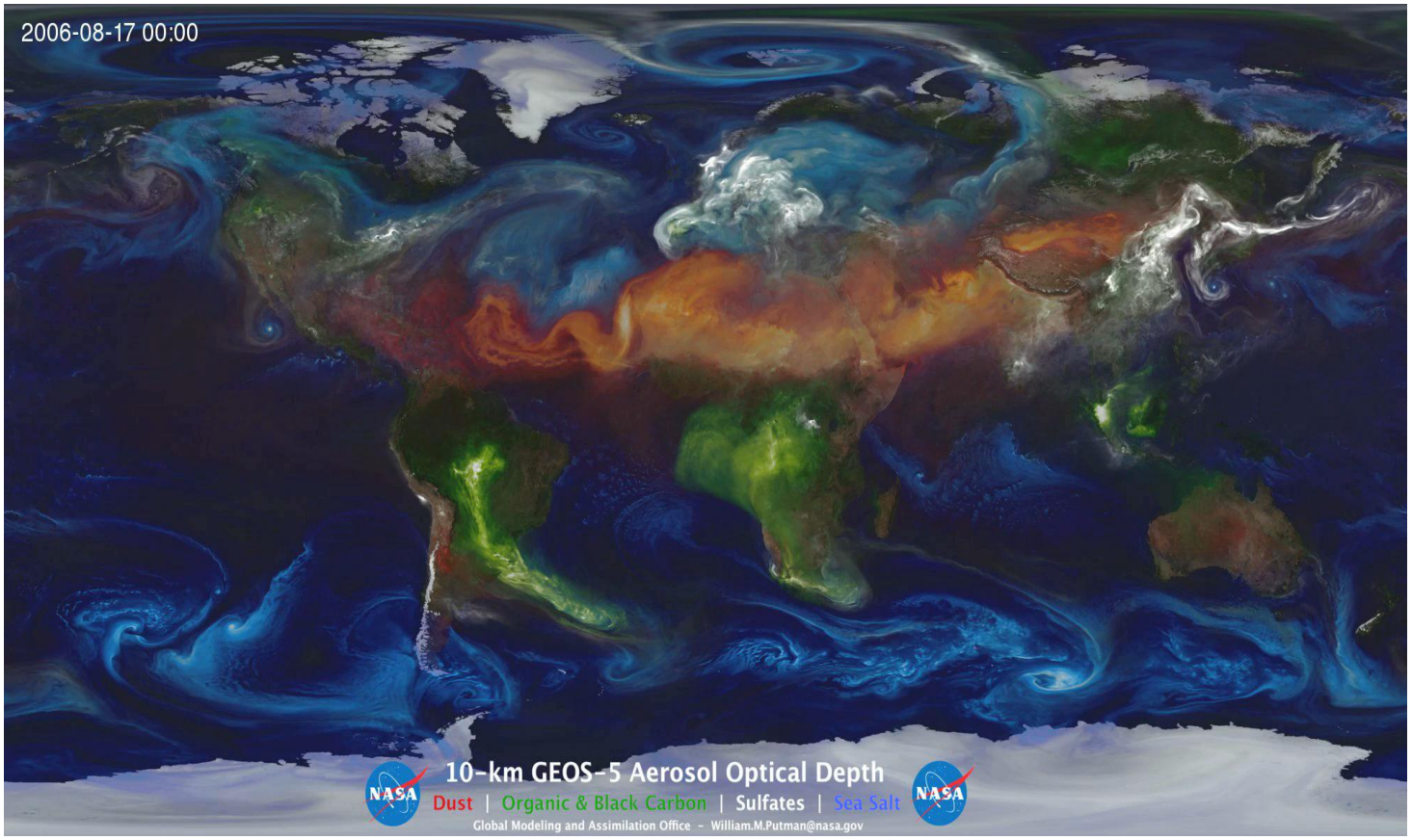
Feedback effect of water vapor and clouds



Richard Lindzen (MIT) postulates that certain gaps (or 'irises') in the cloud cover appear in the tropics as the Earth warms and allows more radiation to escape. This makes the total cloud feedback highly negative. This hypothesis has not stood up well under scrutiny.

The water vapor and cloud feedback are one of the bigger uncertainties in AGW theory. However, direct measurements from Ice Age analysis (as we'll see) indicate the presence of positive feedbacks.

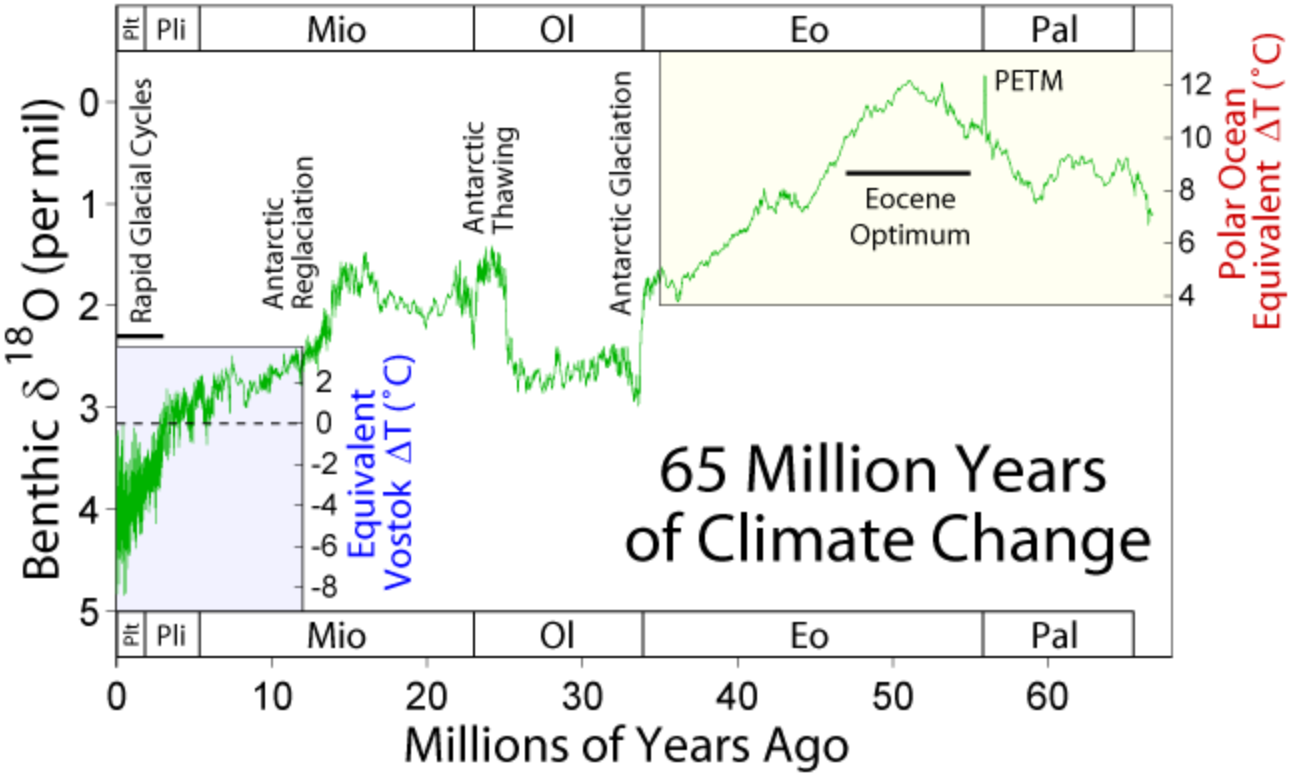
A Movie of the Earth's Aerosols



The extinction optical thickness of aerosols from a free running 10-km GEOS-5 Nature-Run including dust (red), sea salt (blue), black and organic carbon (green) and sulphate (white) are depicted from August 2006 through April 2007. GEOS-5 was run with the GOCART model providing feedbacks of the direct radiative effects of aerosols within the model in addition to their advection by the weather within the simulation.

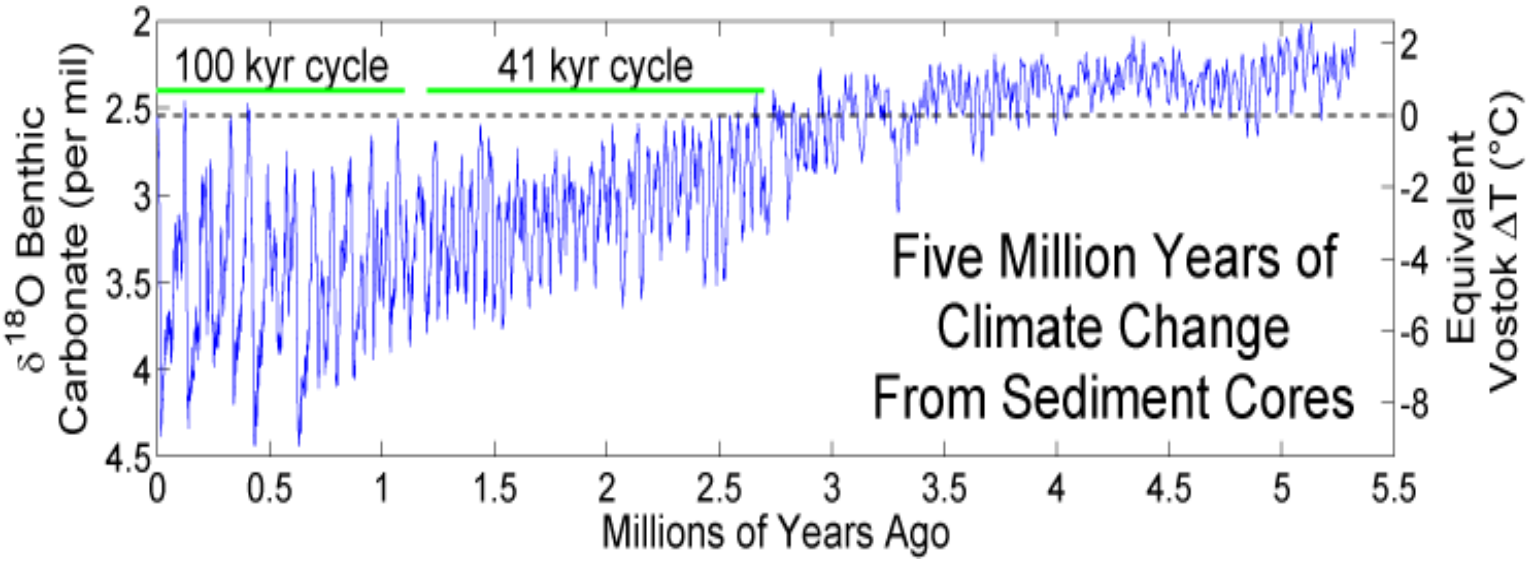
The Ice Ages

History of Earth's Temperature



- Although people think of climate as always changing chaotically, the short story is that the Earth has very long and slow temperature changes and has been steadily cooling for the last 50 million years.
- There is an instability associated with glaciation that gives abrupt 5-7^{o} C changes to the Earth's temperature
- Note the Paleocene-Eocene Thermal Maximum (PETM) during which CO_2 emission rates rivaled those of today.

Ice Ages



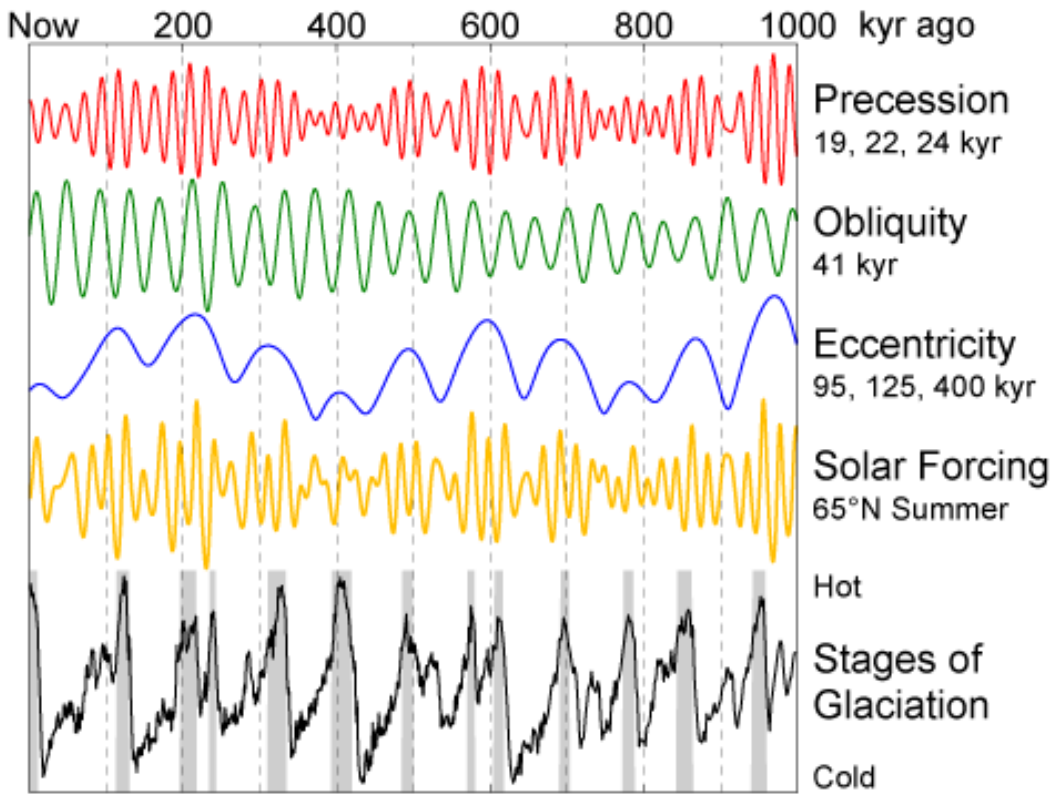
As the planet has steadily cooled in the past 50 million years, an instability has resulted in an oscillatory behavior that has been evident in the last 3 million years.

This is not the typical behavior of the Earth's climate but rather a very special set of circumstances related to the albedo of ice sheets near their positive feedback tipping point

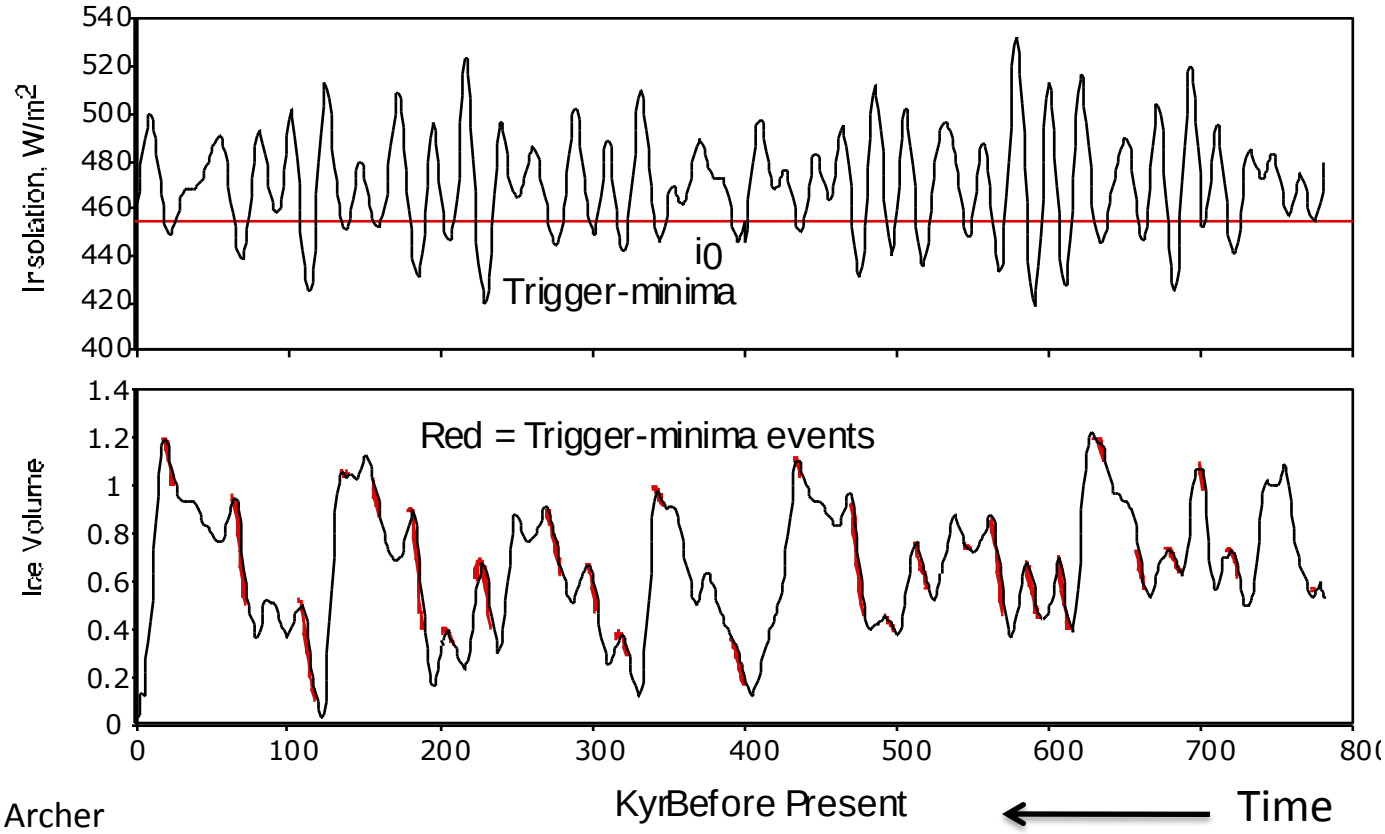
With the inevitable doubling of atmospheric CO_2 due to anthropogenic emissions, and a 3^o C temperature rise, then that means the Ice Ages are probably over. (Yay!)

Milankovitch Cycles

- There is good evidence that the Milankovitch cycles for average solar insolation dictate the timing of the Ice Ages.
- These cycles occur because of the details of the Earth's orbit over a period of tens of thousands of years or so and their effect on solar insolation.
- The Ice Ages are then caused by an amplification mechanism. This amplification mechanism includes the loss of albedo as the ice sheets melt, and the release of greenhouse gases, specifically CO_2, from the ocean.



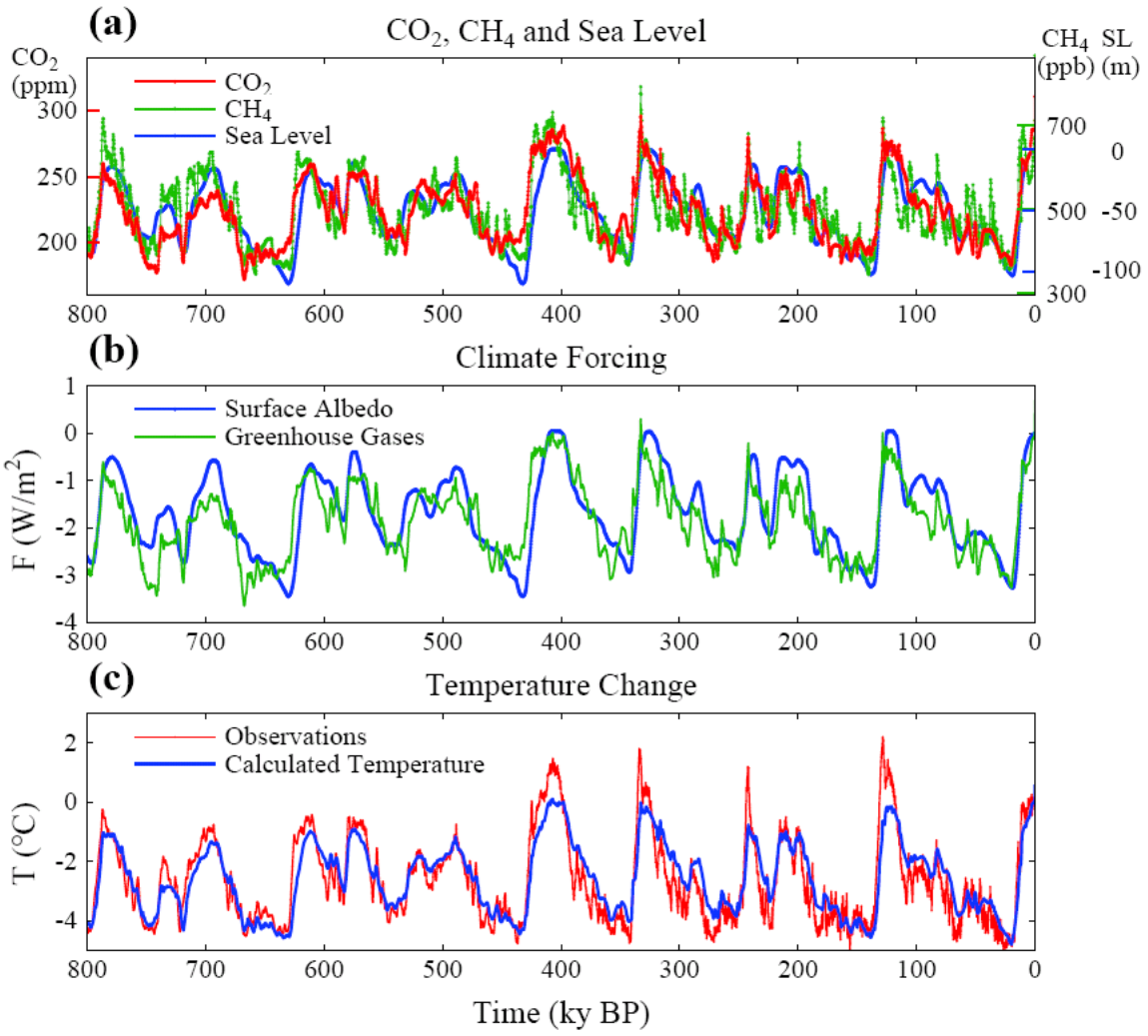
Dim Northern Hemisphere Sun = Growing Ice



Re: David Archer

Very consistent model: when northern latitude average insolation falls below 450 W/m^2, then ice volume starts increasing. Positive feedback mechanisms cause very large temperature excursions.

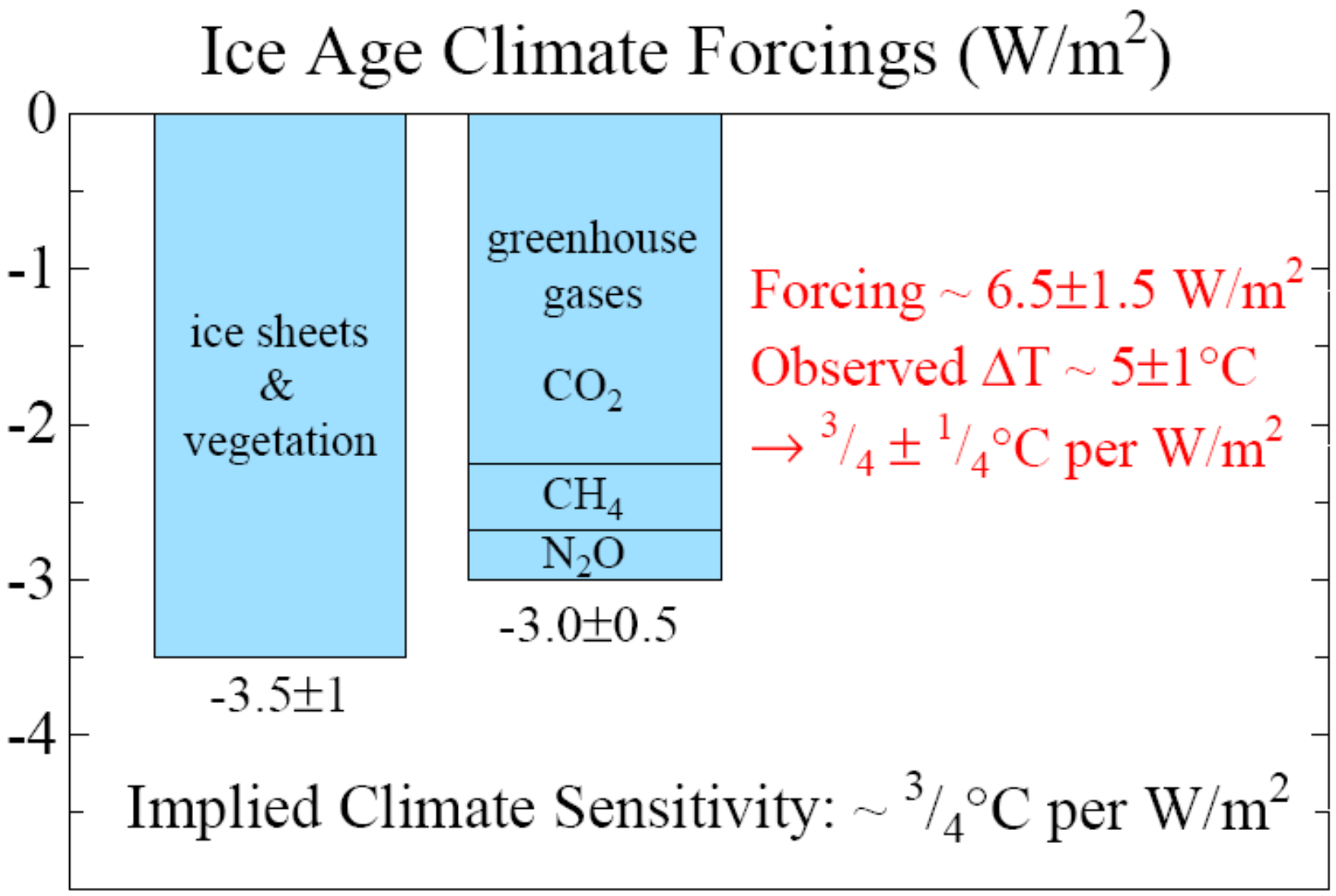
Simple empirical calculation for last 800,000 years (no simulations)

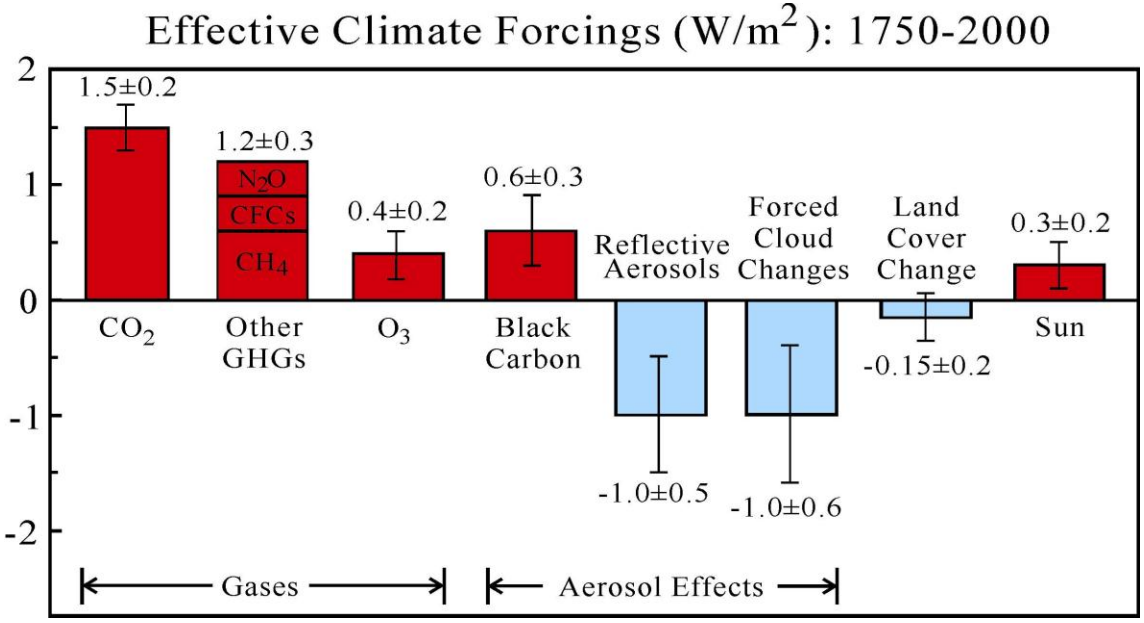


(a) Measured CO_2, CH_4 and sea level for past 800 kiloyears.

(b) Calculated climate forcings due to changes of GHGs and ice sheet area,

(c) Predicted (blue) and observed (red) global temperature change based on above forcings and climate sensitivity of ¾°C per W/m^2. Observations are Antarctic T change divided by two.


Ice Age Climate Forcings (W/m2)
0
-1
-2
-3
-4
ice sheets & vegetation
-3.5±1
greenhouse gases
CO2
CH4
N2O
-3.0±0.5
Forcing ~ 6.5±1.5 W/m2
Observed ΔT ~ 5±1°C
→ 3/4 ± 1/4°C per W/m2
Implied Climate Sensitivity: ~ 3/4°C per W/m2



Climate forcing agents in the industrial era.

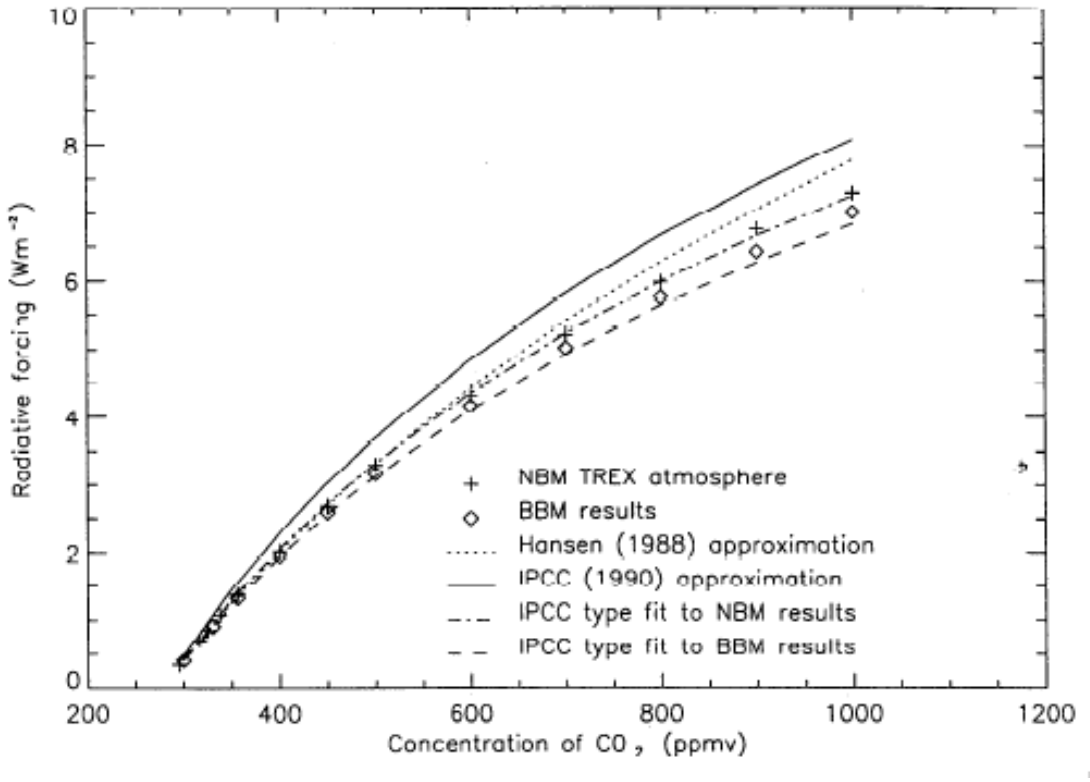
Source: Hansen et al., JGR, **110**, D18104, 2005.

Forcing during the Industrial era has been about 1.9 W/m^2. For a sensitivity of 3/4^o C per W/m^2, as just shown from Ice Age data, we expect a 1.4^o C rise in temperature – which is what we have experienced.

Expected total forcing from doubled CO_2 concentration is 3.7 W/m^2. We can expect a total of at least 2.5^o C rise in global temperature compared to pre-industrial times. Other feedbacks may start up (CH_4 clathrates?)

Greenhouse effect is not linear

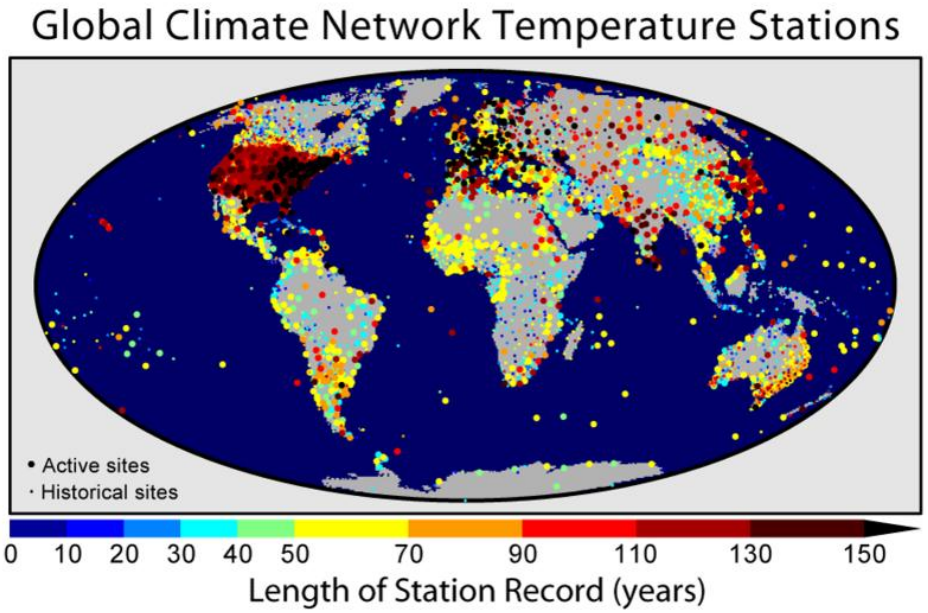
- There is a saturation effect for adding CO_2 and the response is ultimately logarithmic.
- However, this effect is not a substantial correction until well beyond 550 ppm (doubling the pre-industrial concentration)



Measurements of Earth's Temperature

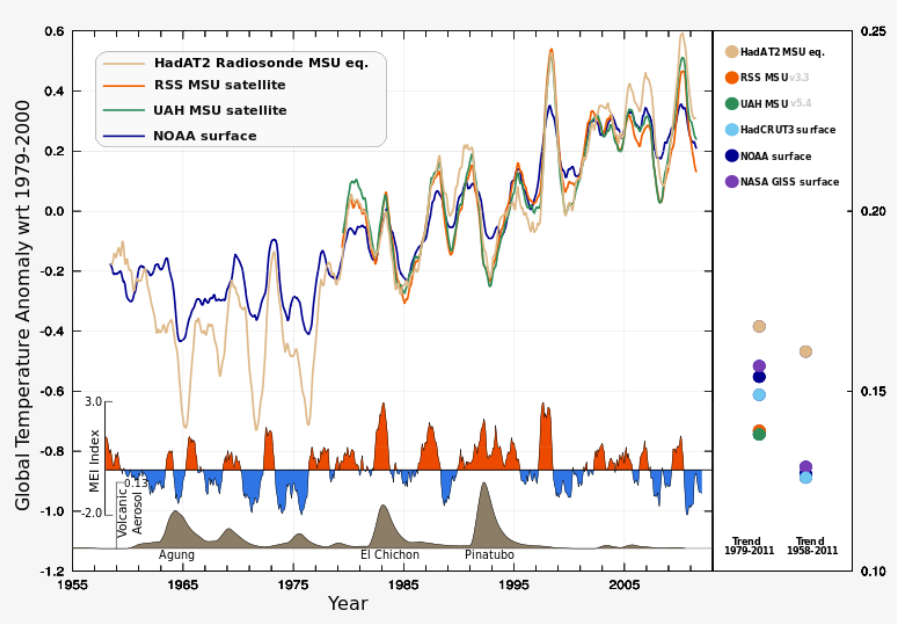
Global Historical Climate Network (GHCN)

- Managed by National Climatic Data Center
- ~7000 temperature stations
- Used for reconstructions of global temperatures by NCDC and GISS (Goddard Institute for Space Studies)
- Oldest continuous record started in 1701.
- Ocean data supplemented by ship records.
- Major enhancements in 1997 to allow for inclusion of max/min data and regional information.
- Time of observation during the day is a significant correction.



Satellite measurements

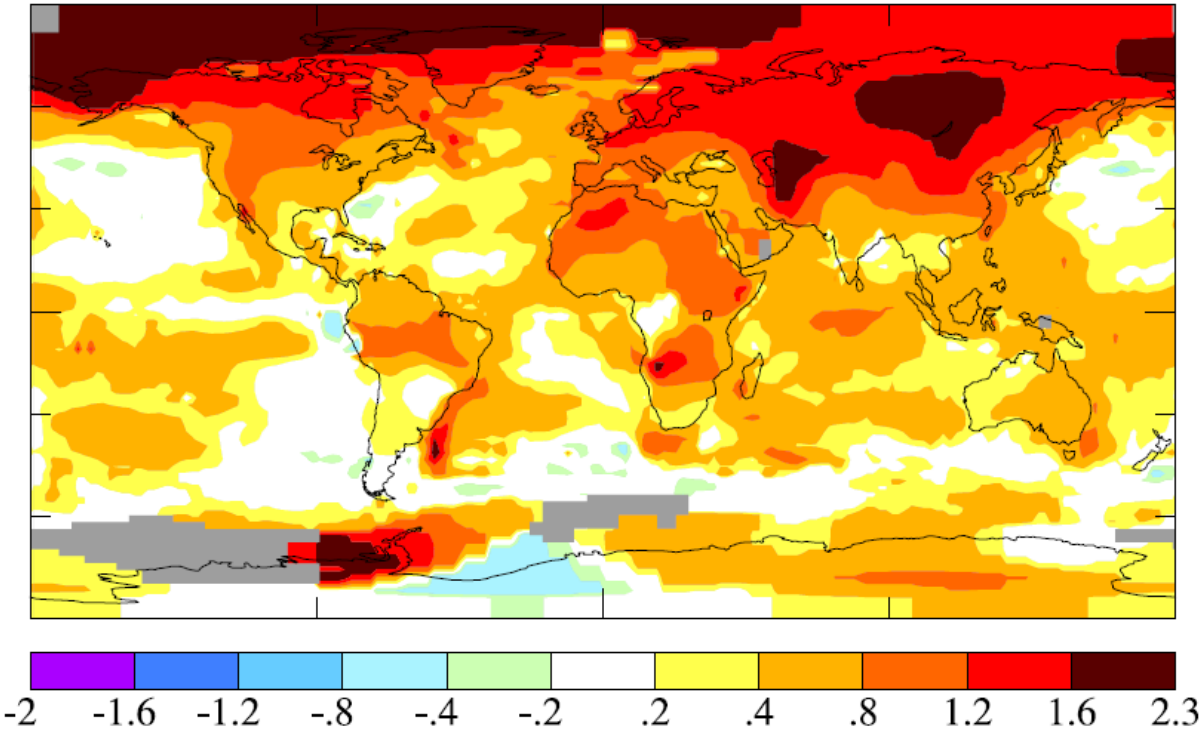
- University of Alabama in Huntsville (UAH) and MSU have made extensive analyses from an ever changing array of satellite measurements of the radiance (W/m^2/steradian) of the Earth and atmosphere.
- Significant corrections need to be made to these data, causing a lot of disagreements and confusion. (Note 1998 orbital decay correction)



UAH version	Main adjustment	Trend correction	Year
A	Simple bias correction		1992
B	Linear diurnal drift correction	-0.03	1994
C	Removal of residual annual cycle related to hot target variation	0.03	1997
D	Orbital decay	0.10	1998
D	Removal of dependence of time variations of hot target temperature	-0.07	1998
5.0	Non-linear diurnal correction	0.008	2003
5.1	Tightened criteria for data acceptance	-0.004	2004
5.2	Correction of diurnal drift adjustment	0.035	2005
5.3	Annual cycle correction	0	2009
5.4	New annual cycle	0	2010

2001-2007 Mean Surface Temperature Anomaly (◦C)

Base Period = 1951-80, Global Mean = 0.54



NASA GISS

- 5 x 5 degree grids are laid on the surface
- Each temperature record is changed to an 'anomaly' series, after making various corrections
- Anomalies are averaged within the grid boxes
- Anomalies from without the grid box are weighted by their distance
- Empty grid boxes are interpolated from surrounding boxes

Are There Systematic Effects Biasing the Recent Temperature Record?

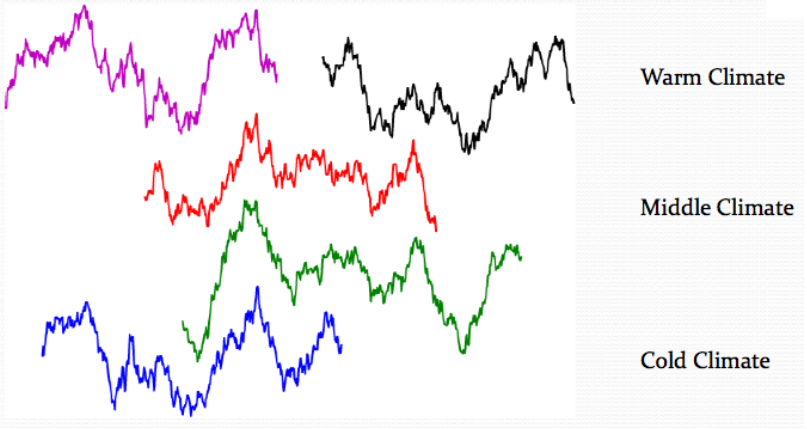
- Many insist that as cities and their 'urban heat islands' have grown in size, any local temperature sensors will record an artificial increase.
- There are many temperature sensor locations that are obviously flawed (near air conditioning exhausts, parking lots, etc.), but most aren't.
- A self-described 'skeptic' Berkeley professor – Richard Muller – embarked on a complete reanalysis of the temperature record:

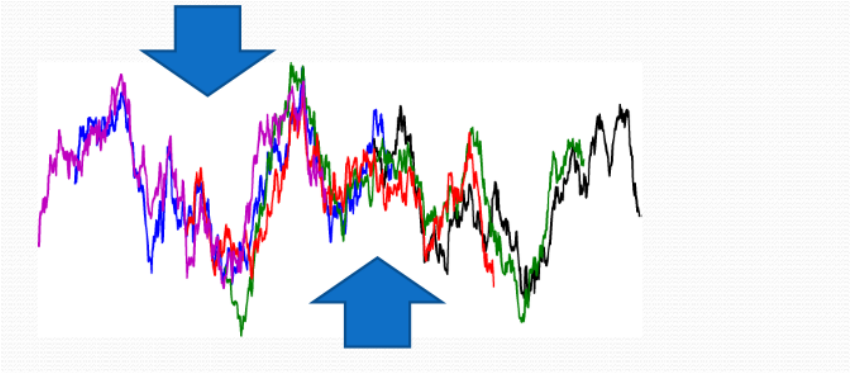
'BEST' = 'Berkeley Earth Surface Temperature project'

Dataset	Berkeley Earth	GHCN-M v3
Number of Stations	39,028	7,280
Monthly Observations	14,786,160	5,150,496
Median Record Length	25.8 Years	58.5 Years

Assembling the Record

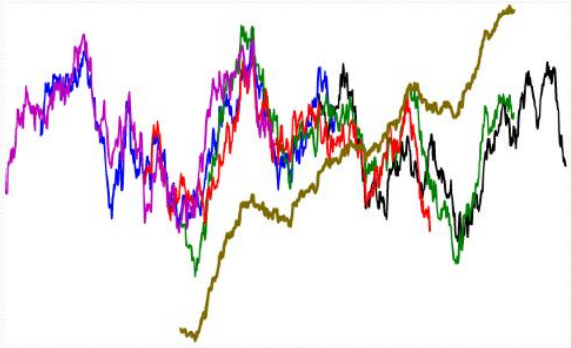
Local factors such as latitude and elevation have a very large effect on the mean climate at each site





Integrated Outlier / Reliability Assessment

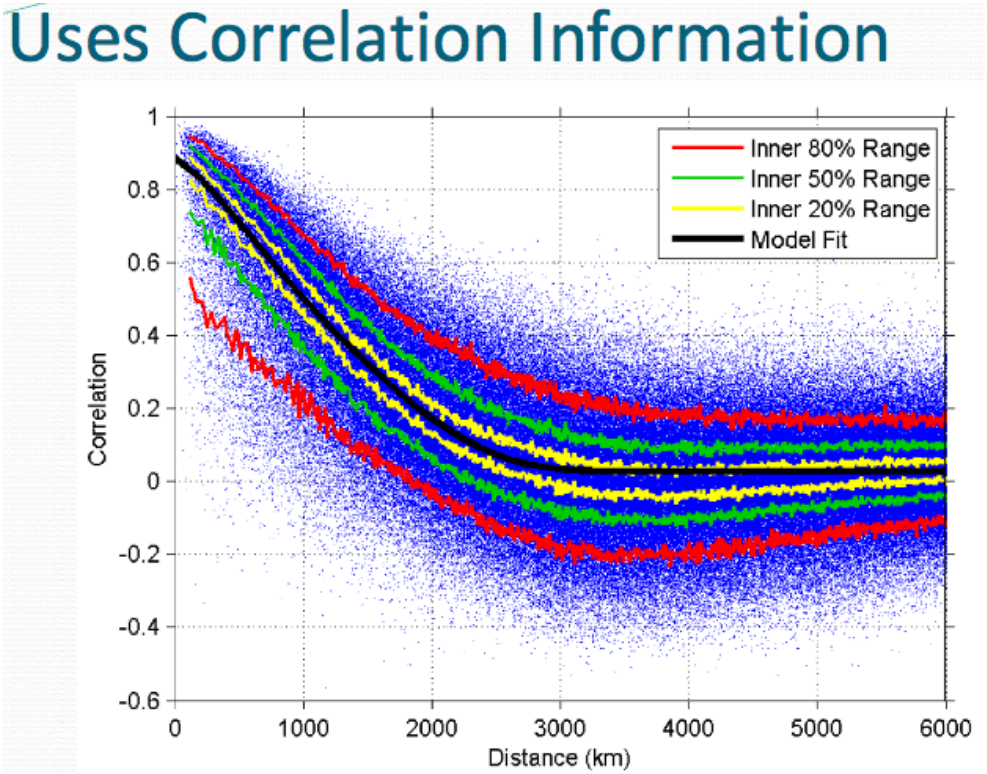
- Highly anomalous series are also deweighted



- Each partial record is corrected for latitude and elevation
- Partial records are stitched together by other partial records
- Standard statistical tests are made on each record and obvious outliers are deweighted
- No gridding is performed, but global average is calculated

Correlations of temperature span huge distances !

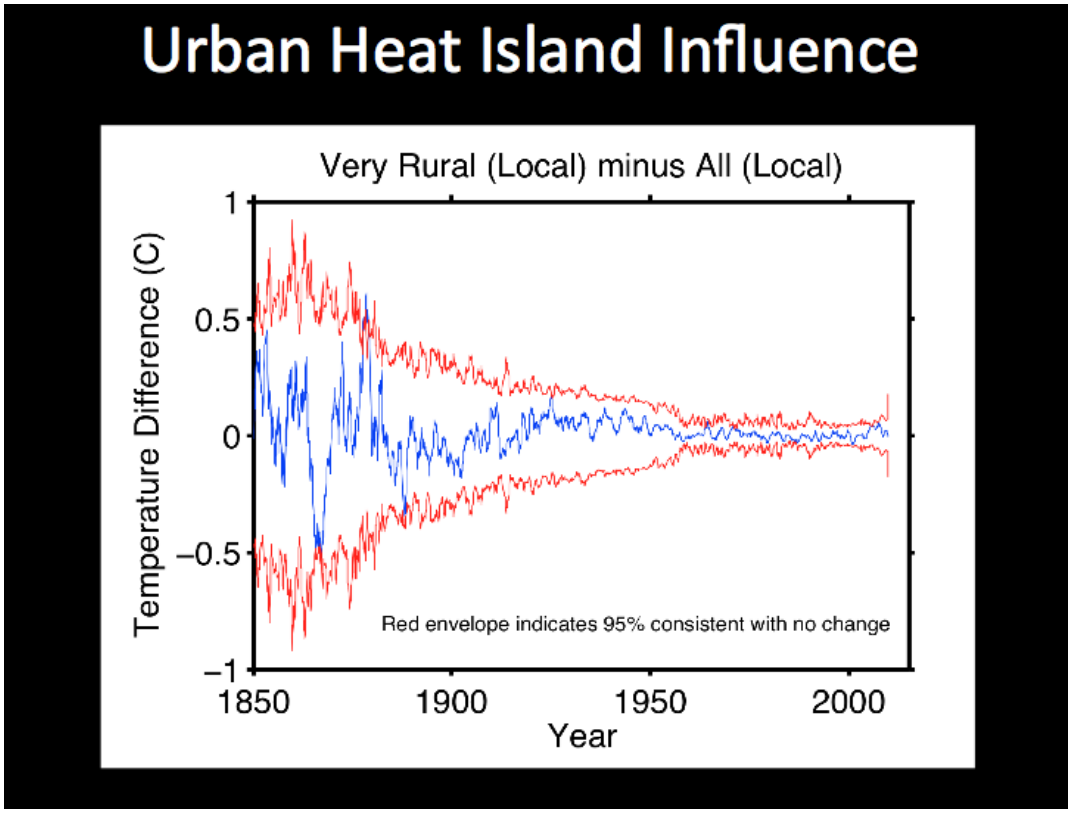
- BEST measurements confirm that temperature sensors are highly correlated, even on the scale of 1000 km
- For any point on the globe, you can weight the data averaging using this correlation.
- As little as 200 sensors, placed strategically around the globe, could give an accurate measure of the global average temperature.



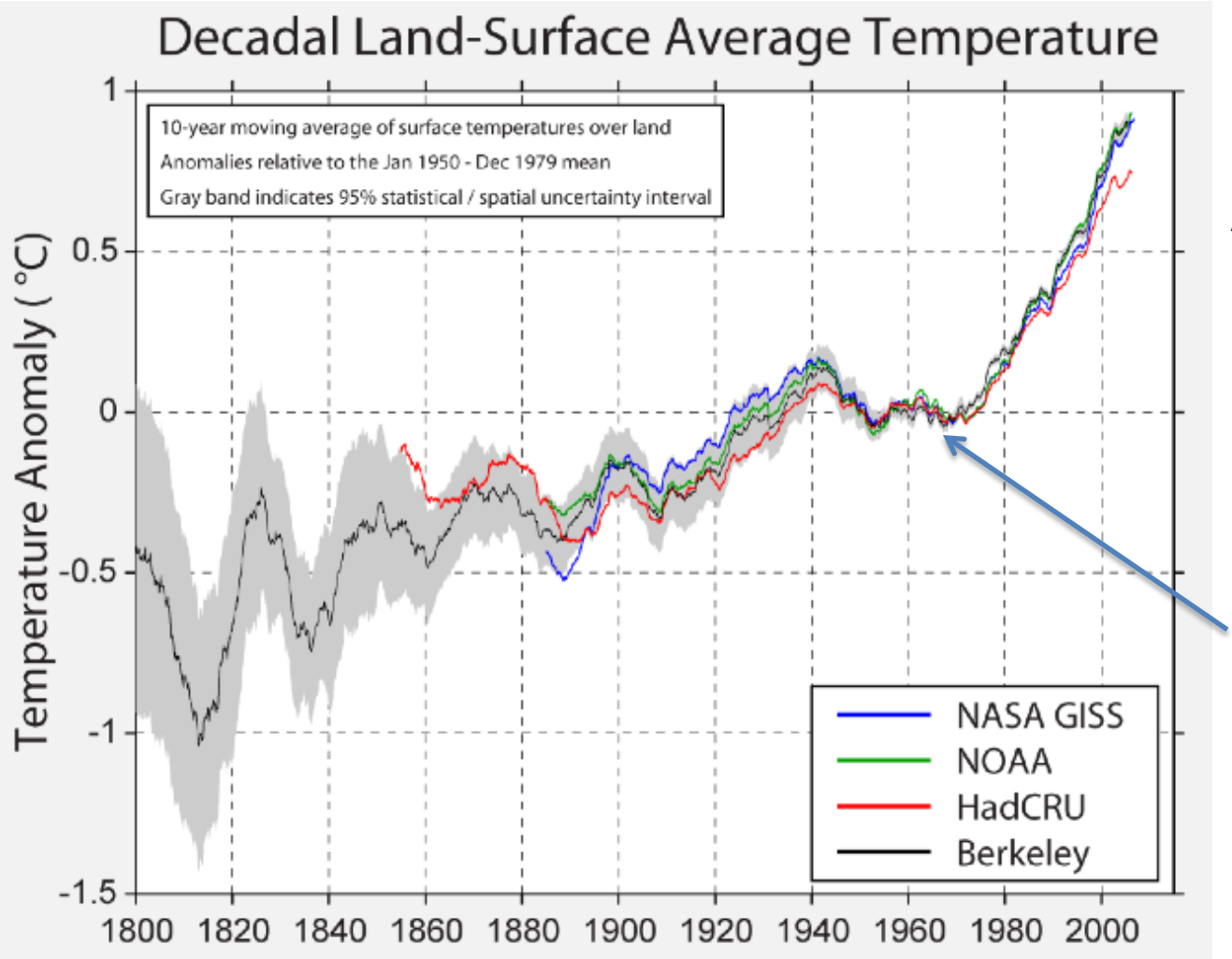
No urban vs rural systematic effect exists

Rural sited meteorological station

Urban sited meteorological station



BEST final result



(HadCRU does not include Arctic regions!)

1940-1970 was a time of heavy aerosols in the atmosphere

Corrections to the global average temperature record

Table 2: Trends in °C/decade of the signal components due to MEI, AOD and TSI in the regression of global temperature, for each of the five temperature records from 1979 to 2010.

	MEI	AOD	TSI
GISS	−0.014	0.025	−0.014
NCDC	−0.014	0.019	−0.017
CRU	−0.015	0.020	−0.019
RSS	−0.022	0.038	−0.023
UAH	−0.023	0.041	−0.018

Foster and Rahmstorf(2011)

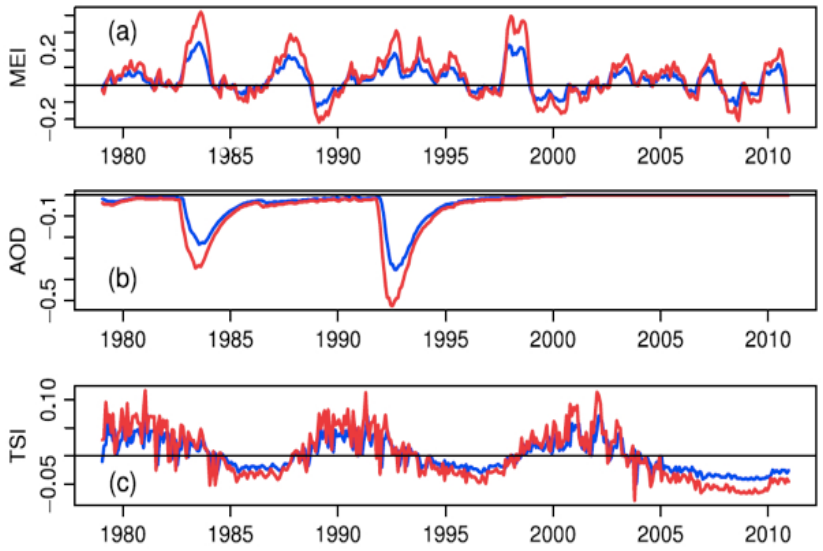


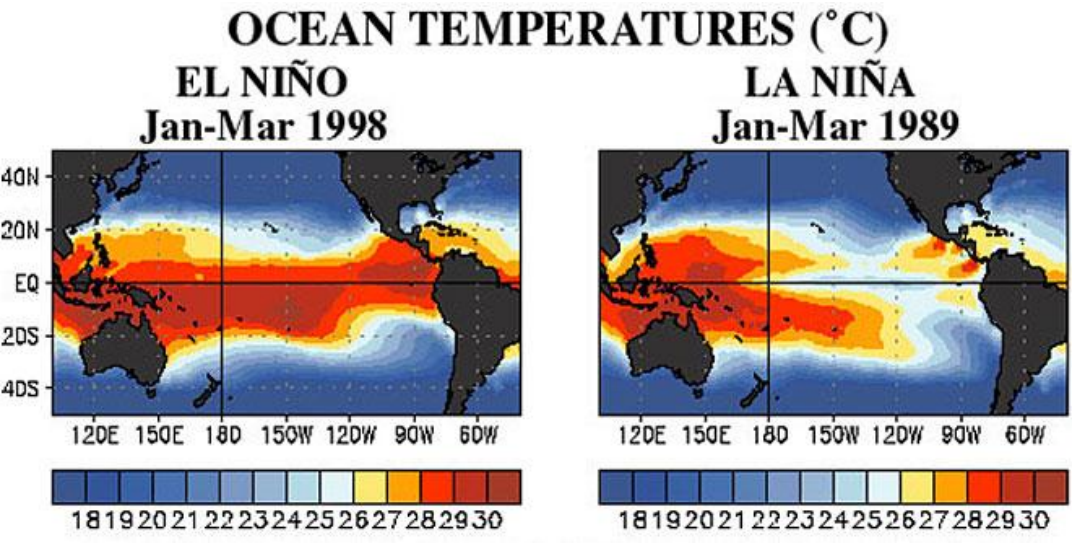
Figure 2: Influence of exogenous factors on global temperature for GISS (blue) and RSS data (red). (a) MEI; (b) AOD; (c) TSI.

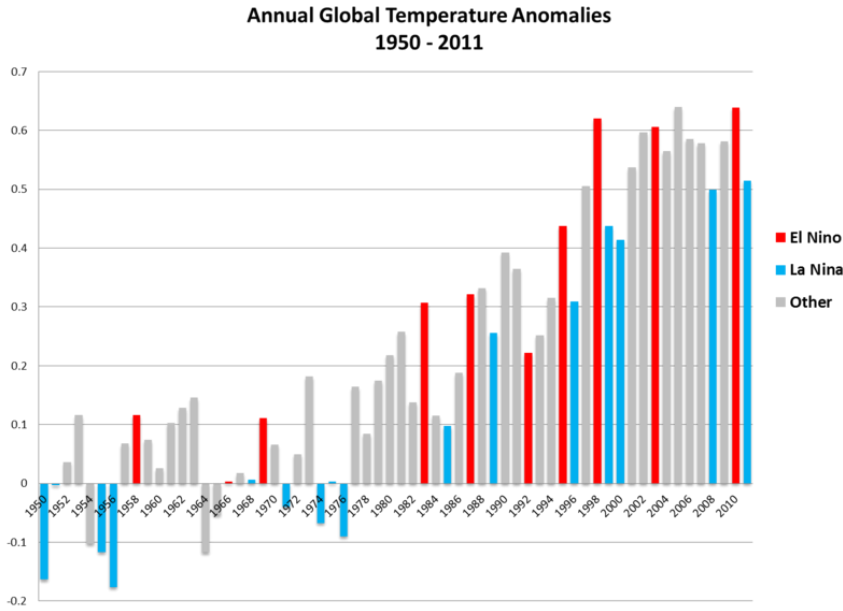
MEI = Multivariate ENSO Index
(ENSO=El Nino Southern Oscillation)

AOD = Aerosol Optical Thickness

TSI = Total Solar Irradiance

El Nino & La Nina – The Southern Pacific Oscillation



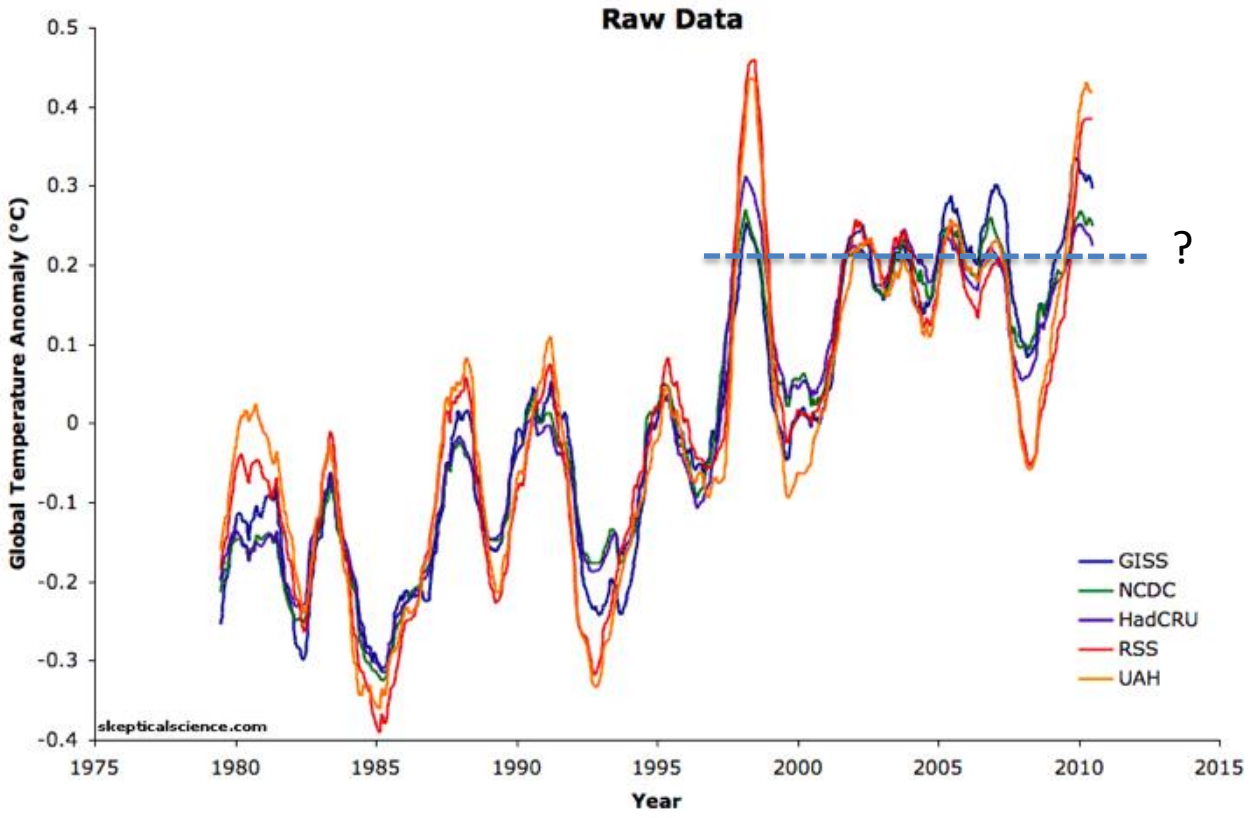


El Nino: High atmospheric pressure in the western Pacific causes heat flow eastward. La Nina is the reverse.

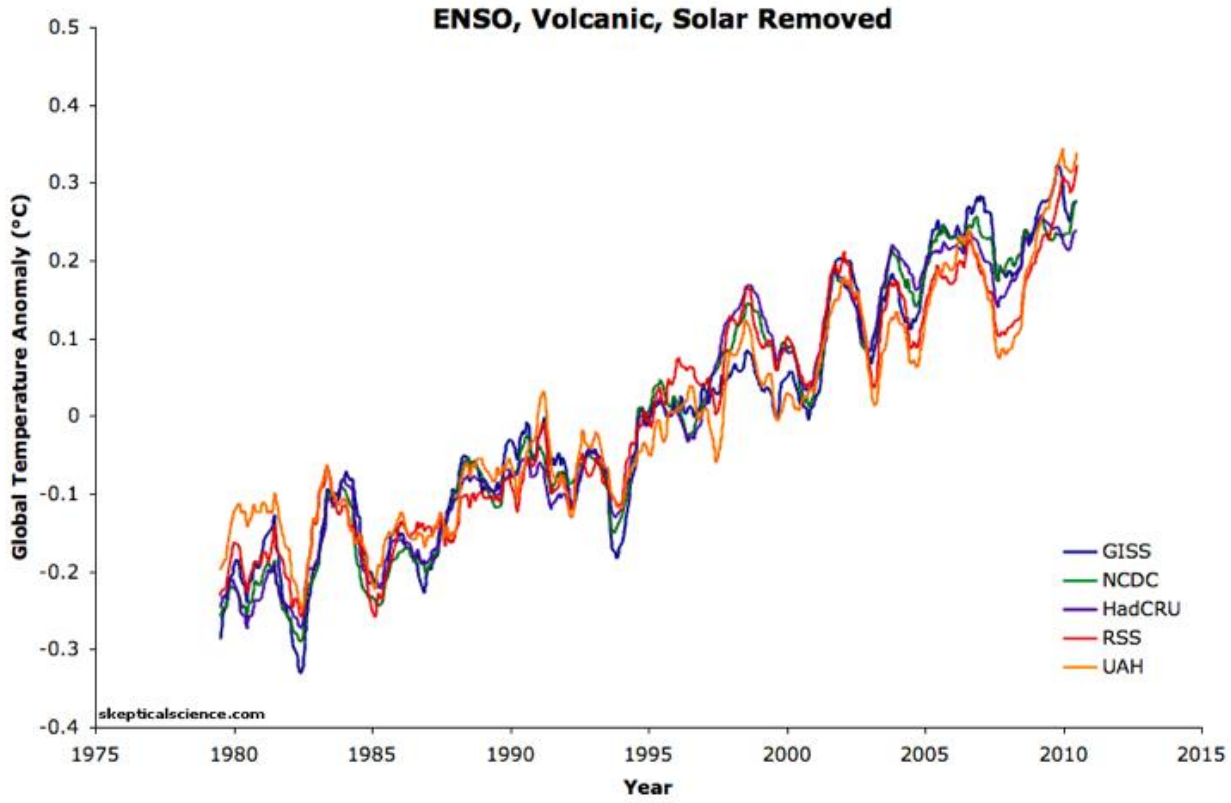
These episodes are correlated to global temperatures at the 0.2° C level and can be corrected for in global averages.

These oscillations are not related to global warming, (first observed in the 1600's) but do introduce a noise source

Has Global Warming Stopped in the last 15 years?

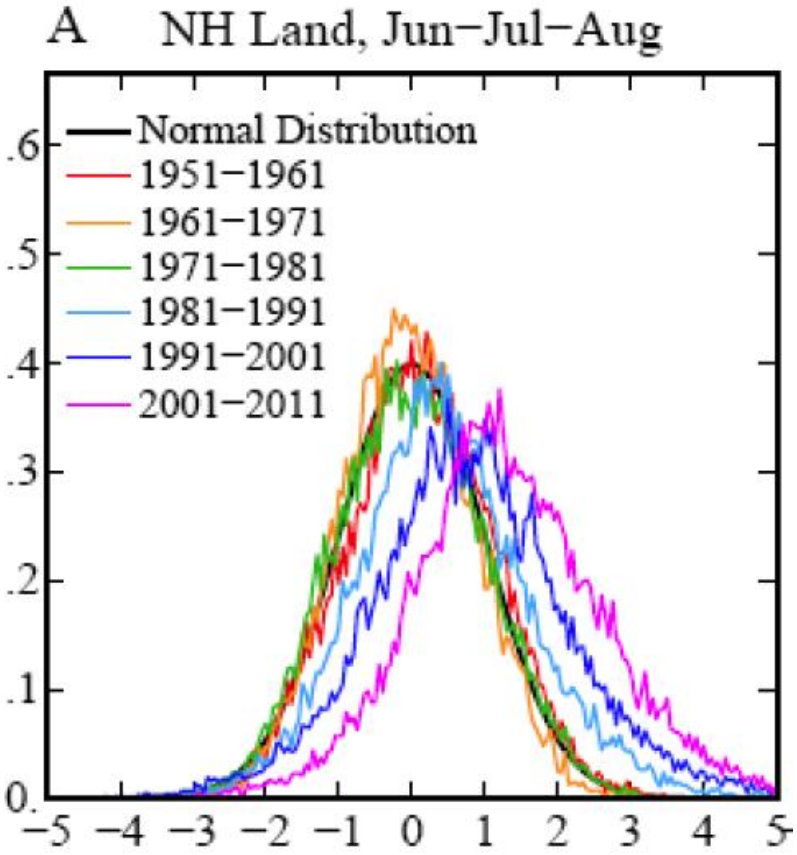


Anthropogenic Global Warming is Continuing at a Steady Pace



Calculation of Anomaly Distributions by Decade

- Baseline the temperatures in 1951-1961 to Gaussian
- Plot average temperature anomalies with respect to this base period.
- As shown, extreme heat events have become much more common – at the 4-5 σ level.
- Heat waves that are causing tens of thousands of people to die are, indeed, a direct result of AGW.



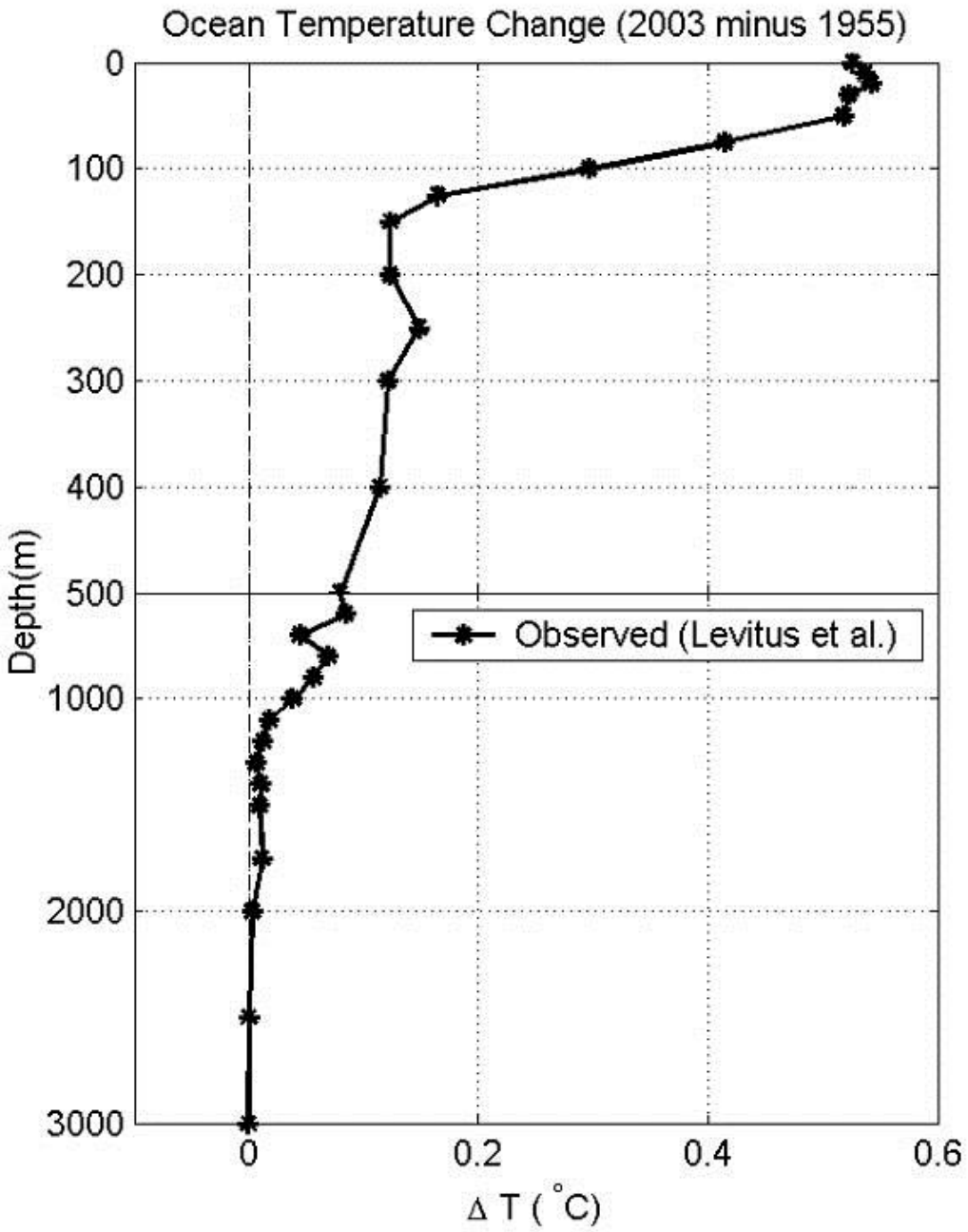
Ref: J. Hansen (2011)

Water and Ice

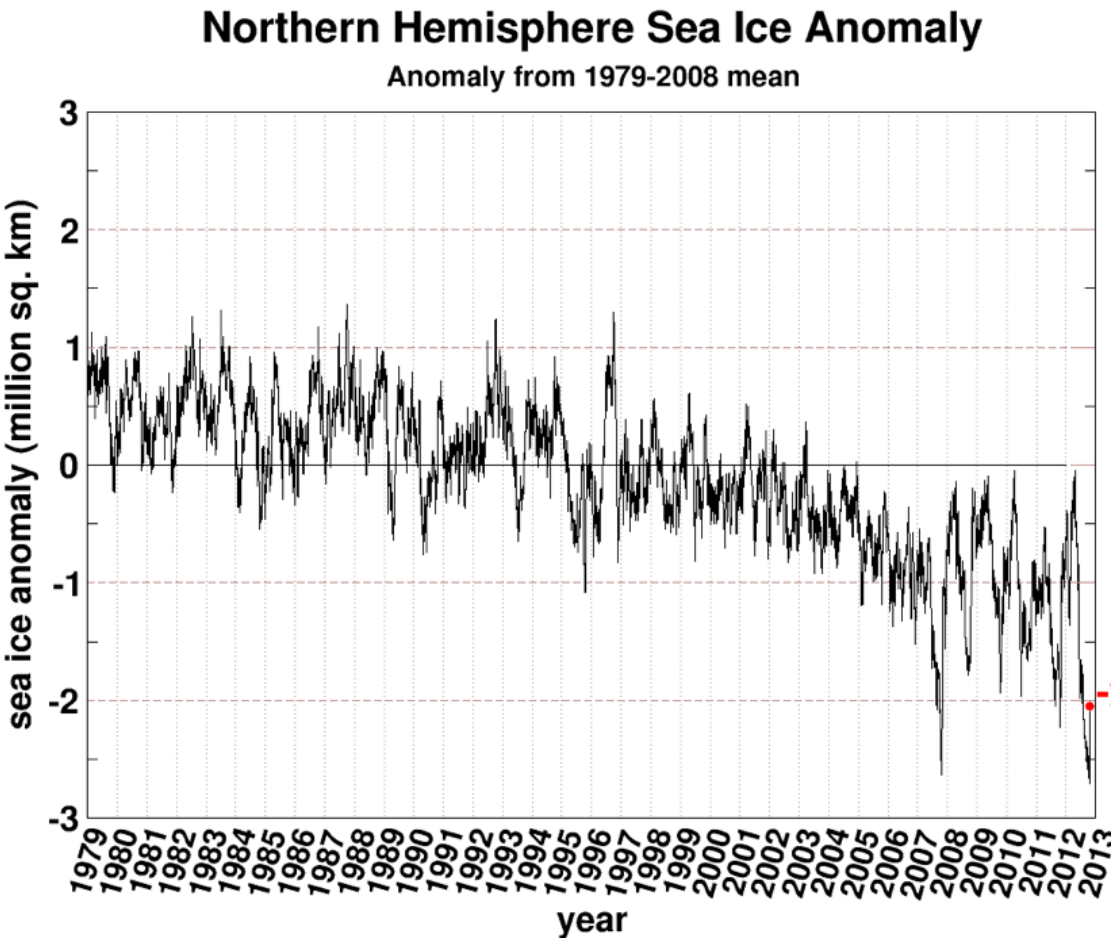
The ocean is absorbing a large fraction of the warming.

What happens when the deep ocean equilibrates with the surface?

Then the forcing from GHG's will have a more intense effect.



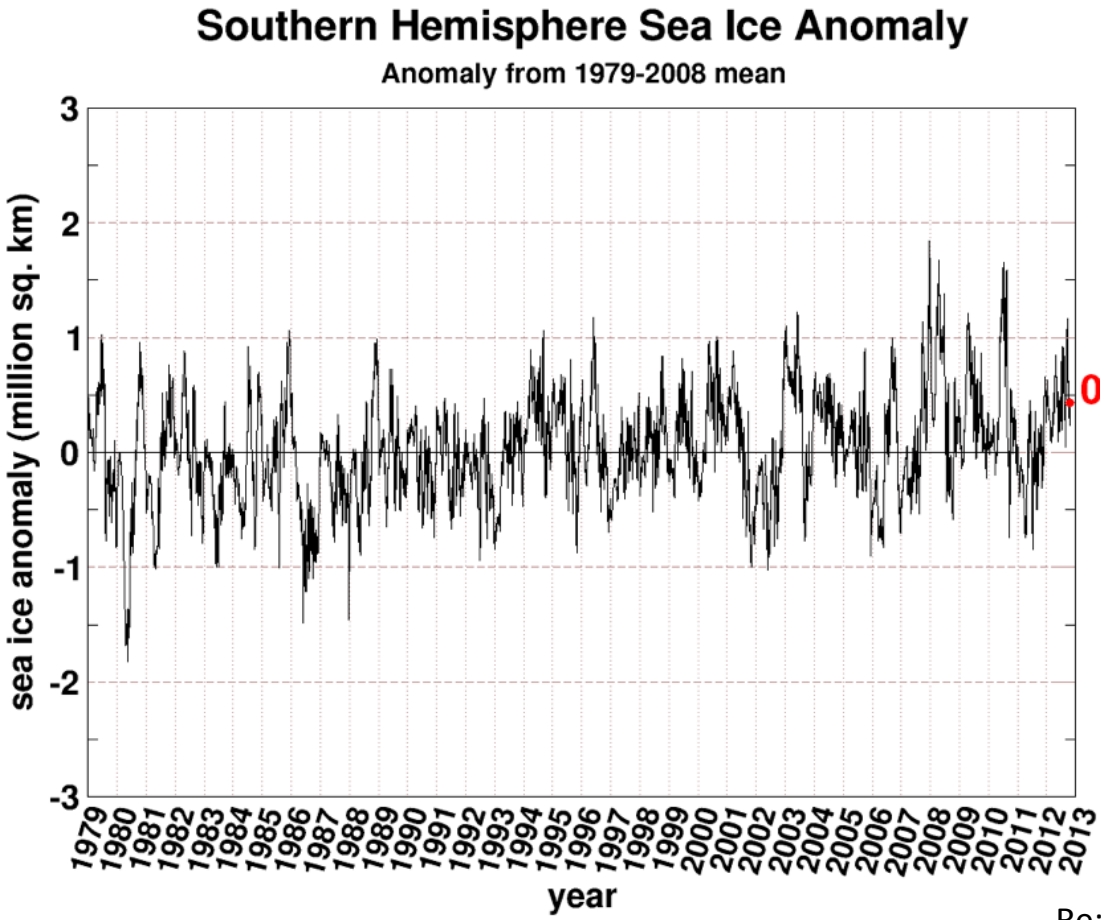
Arctic Sea Ice Area



Re: Cryosphere Today

Sea ice area reached a new absolute minimum in 2012

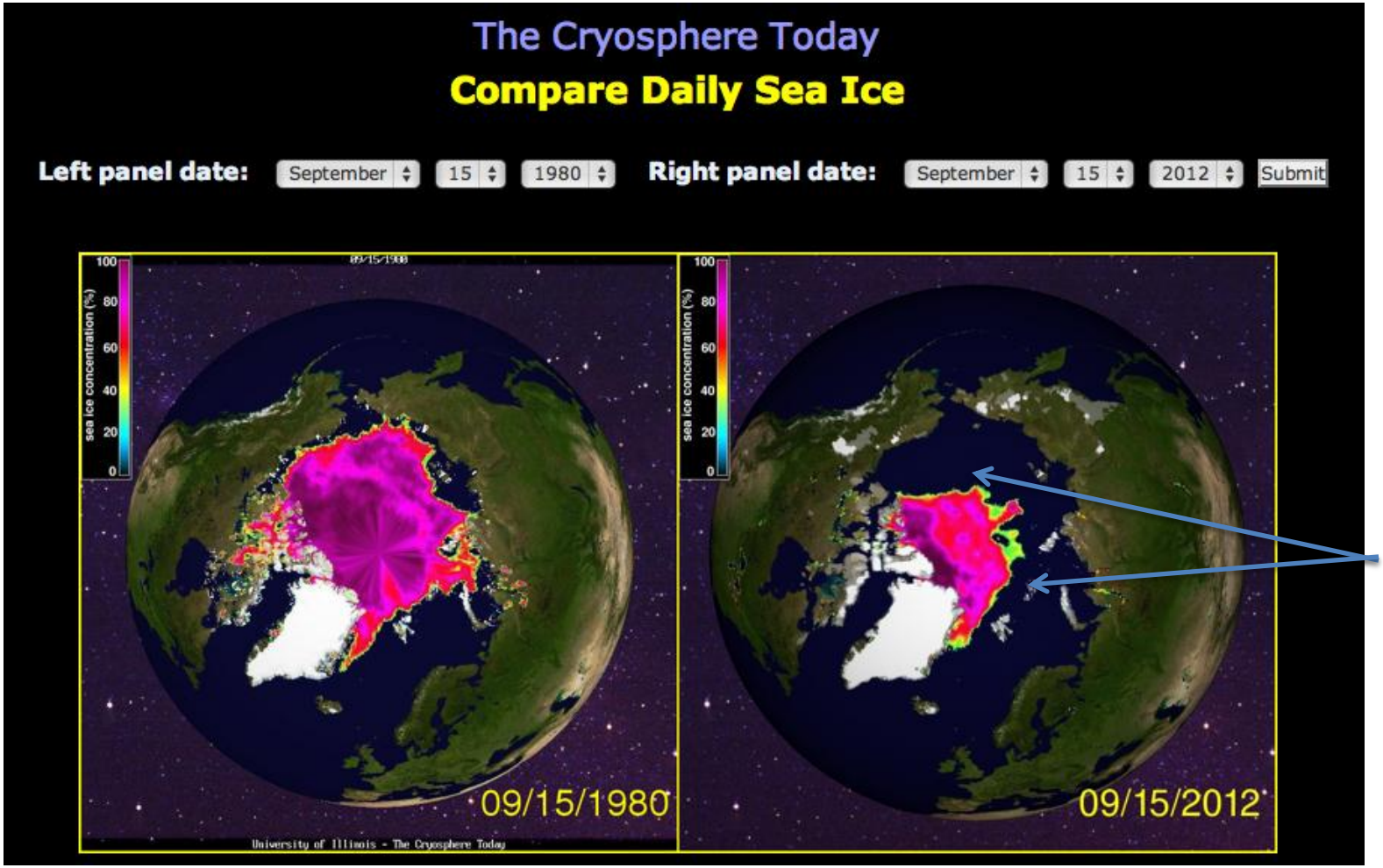
Antarctic Ice Area



Re: Cryosphere Today

- Antarctica is buffered by an extremely large land ice mass
- There is a modest increase in sea ice area, but this does not match Arctic losses

We are rapidly transitioning to a world without permanent Arctic Ice

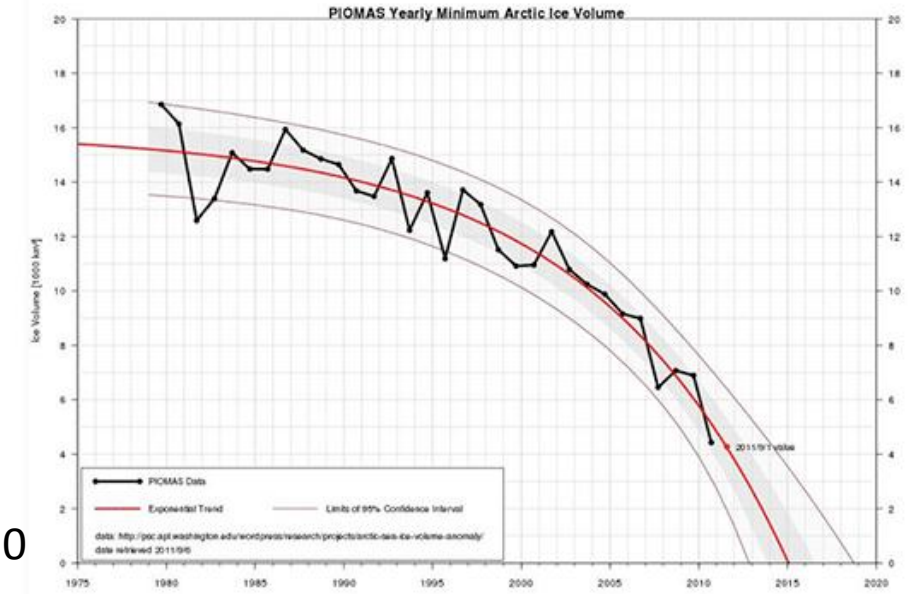


Note reduction in albedo for this large area

To understand the drastic nature of what is happening in the Arctic regions, it's Important to Concentrate on Volume, not Area !

PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System – U. Washington) is a model that uses estimates for sea ice thickness and then calculates ice volume

20,000 km^3

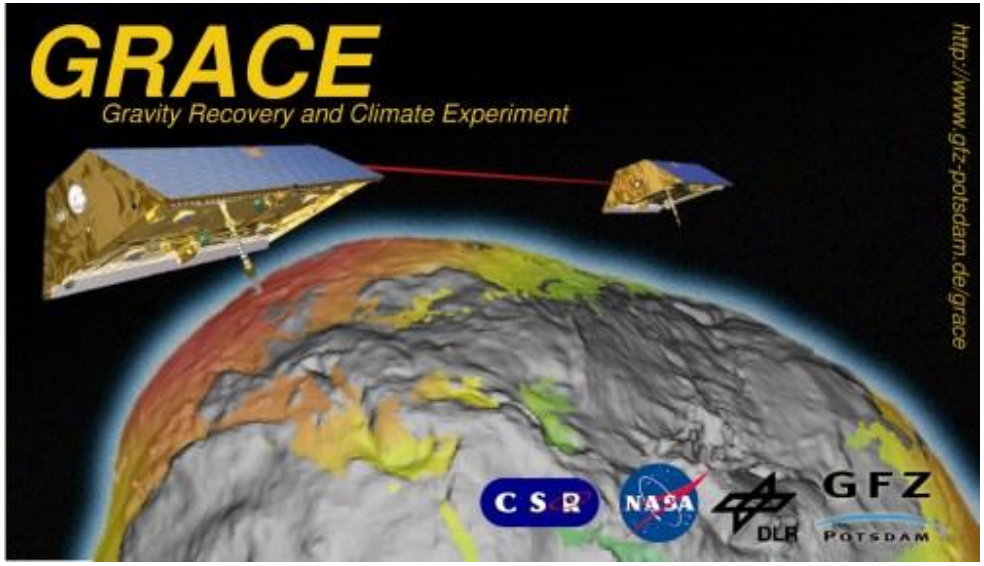


0

1980

2015

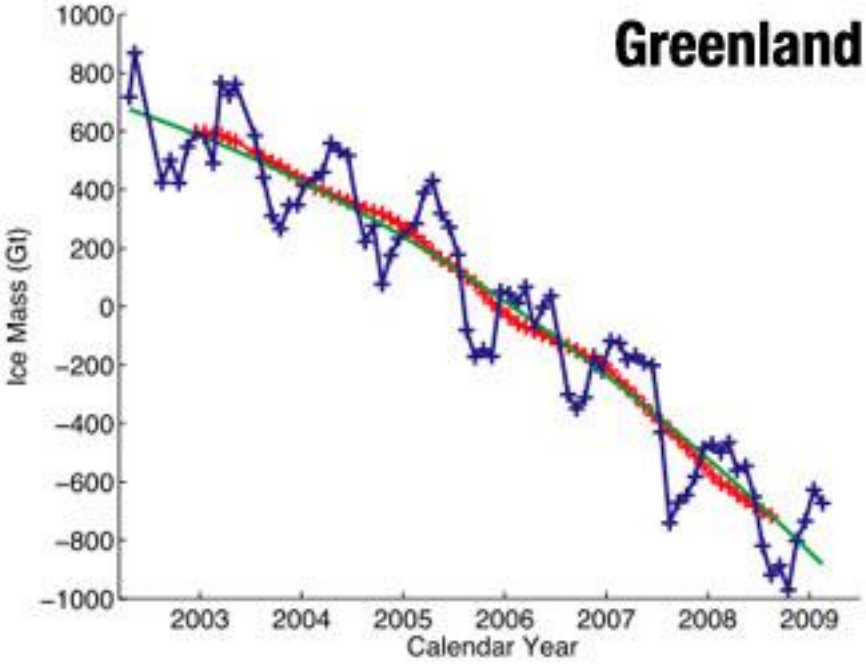
Determining Ice Sheet Mass by Satellite

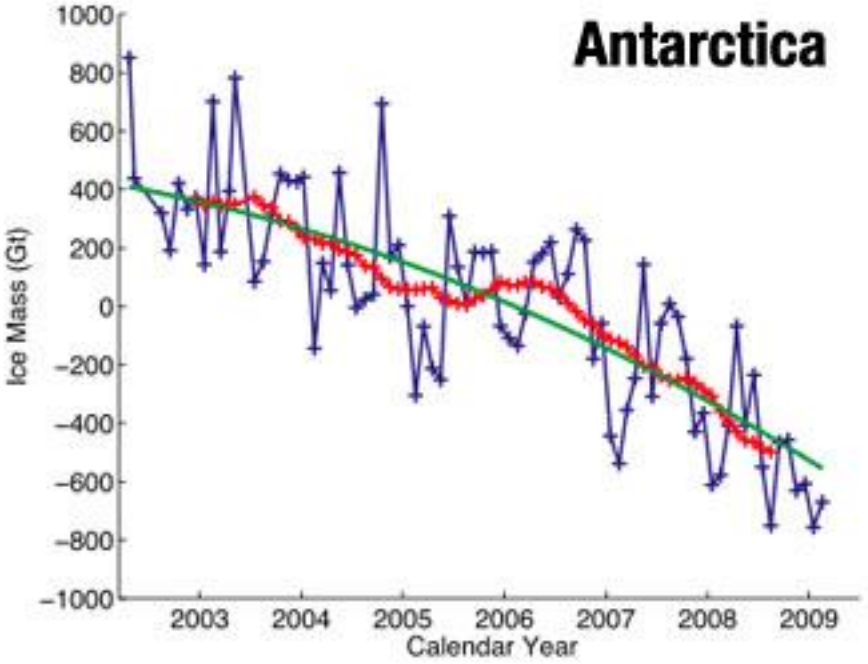


GRACE is a pair of polar orbiting satellites, monitored by GPS, which can make systematic studies of the gravity field of the Earth

This has been an extraordinarily useful facility, in many fields of study, one of which is studying the amount of ice that is resident in Greenland and Antarctica.

Results from the GRACE satellites





Loss in Arctic icecap averaged over the last 30 years is of the same order

The Future

Scenarios of Future Warming

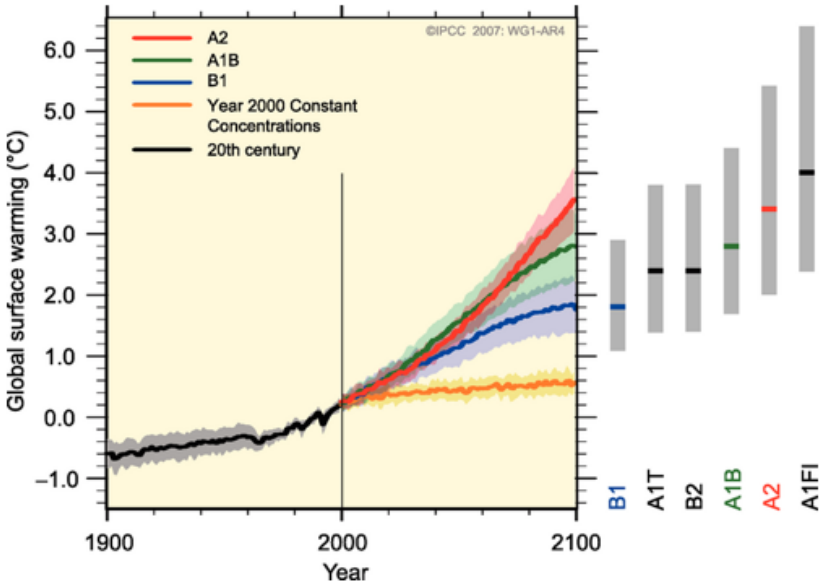
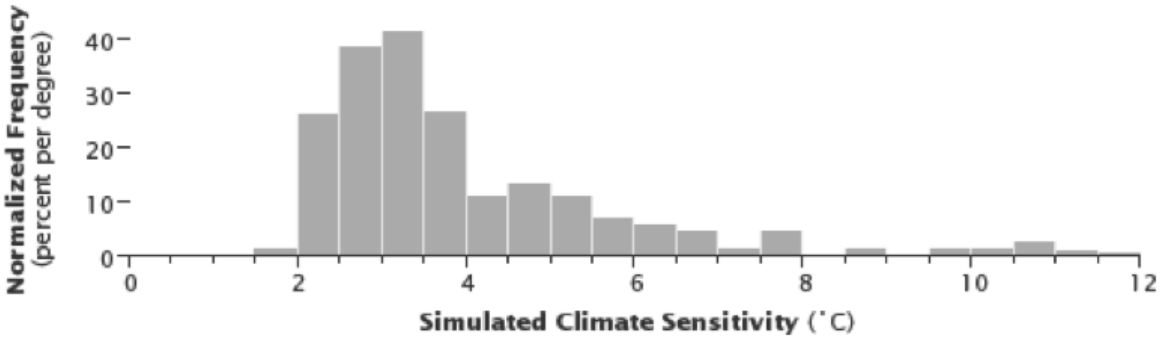


Figure 2: Global surface temperature projections for IPCC Scenarios. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is constant CO2 concentrations at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range. (Source: IPCC).

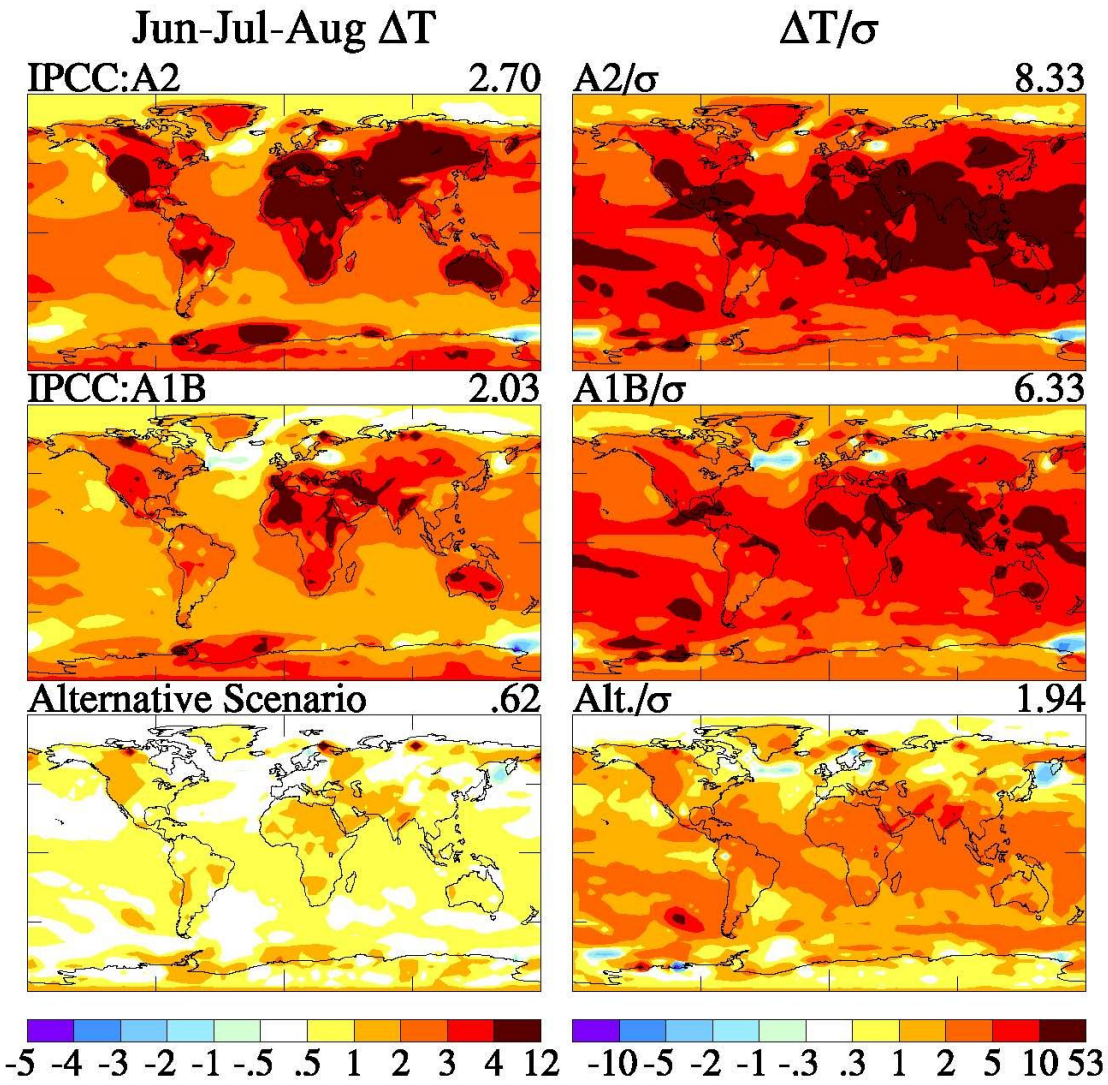


Predicted sensitivities from climate models. A 5° C sensitivity would be on the order of a 15σ effect

Simulated 2000-2100 Temperature Change

σ is interannual standard deviation of observed seasonal mean temperature for period 1900-2000.

Source: Hansen et al., *J. Geophys. Res.*, submitted.



Much of the land surface will experience extreme floods or drought

Projections and model consistency of relative changes in runoff by the end of the 21st century

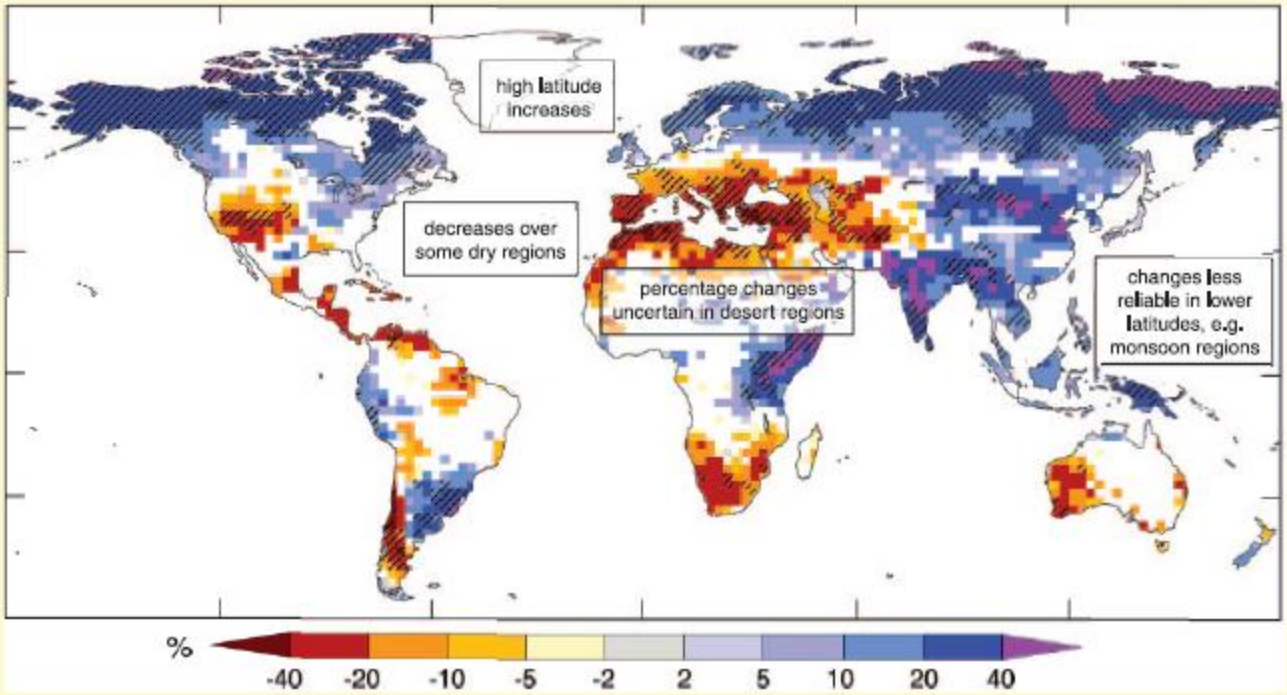
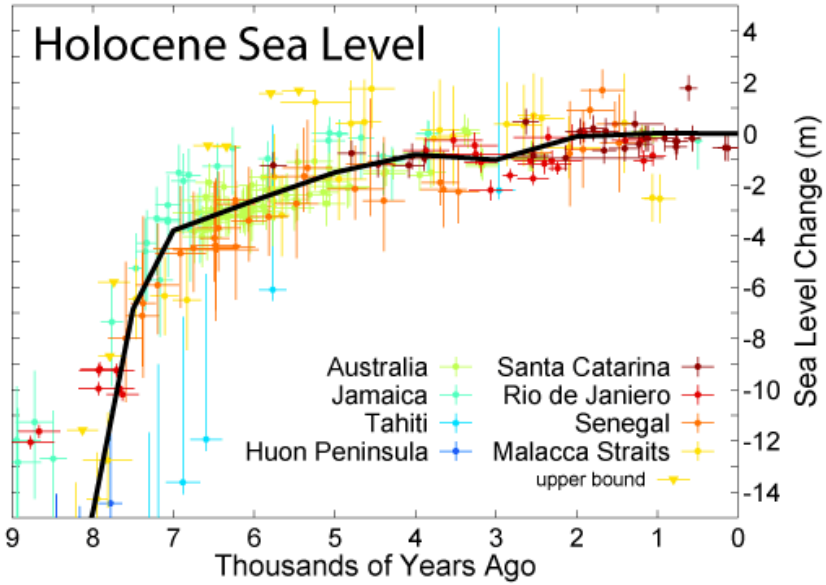
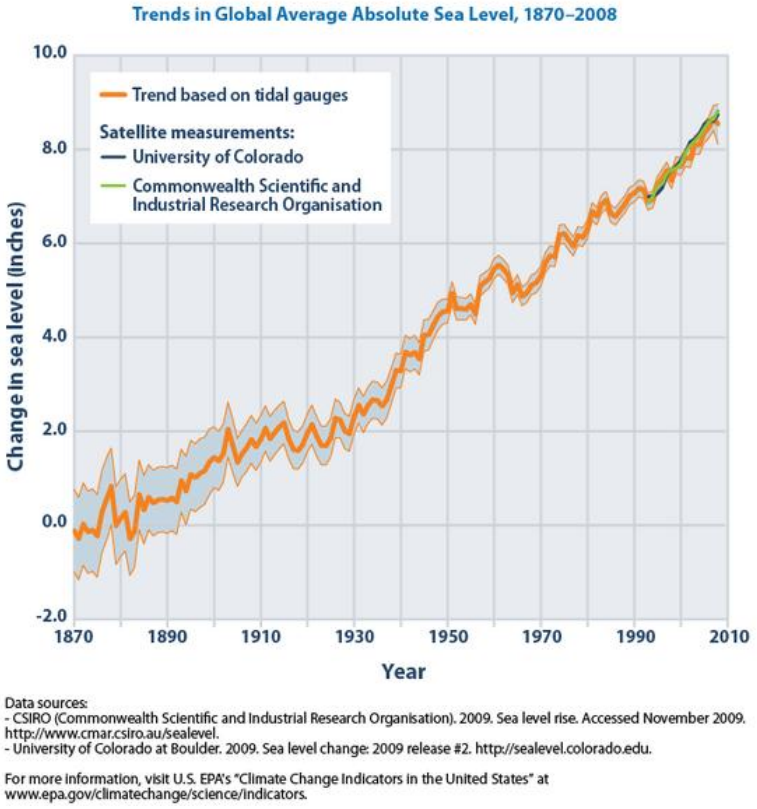


Figure 3.5. *Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. The quality of the simulation of the observed large-scale 20th century runoff is used as a basis for selecting the 12 models from the multi-model ensemble. The global map of annual runoff illustrates a large scale and is not intended to refer to smaller temporal and spatial scales. In areas where rainfall and runoff is very low (e.g. desert areas), small changes in runoff can lead to large percentage changes. In some regions, the sign of projected changes in runoff differs from recently observed trends. In some areas with projected increases in runoff, different seasonal effects are expected, such as increased wet season runoff and decreased dry season runoff. Studies using results from few climate models can be considerably different from the results presented here. {WGII Figure 3.4, adjusted to match the assumptions of Figure SYR 3.3; WGII 3.3.1, 3.4.1, 3.5.1}*

Sea Level Rise: Storm Surges are Highly Sensitive to this Value

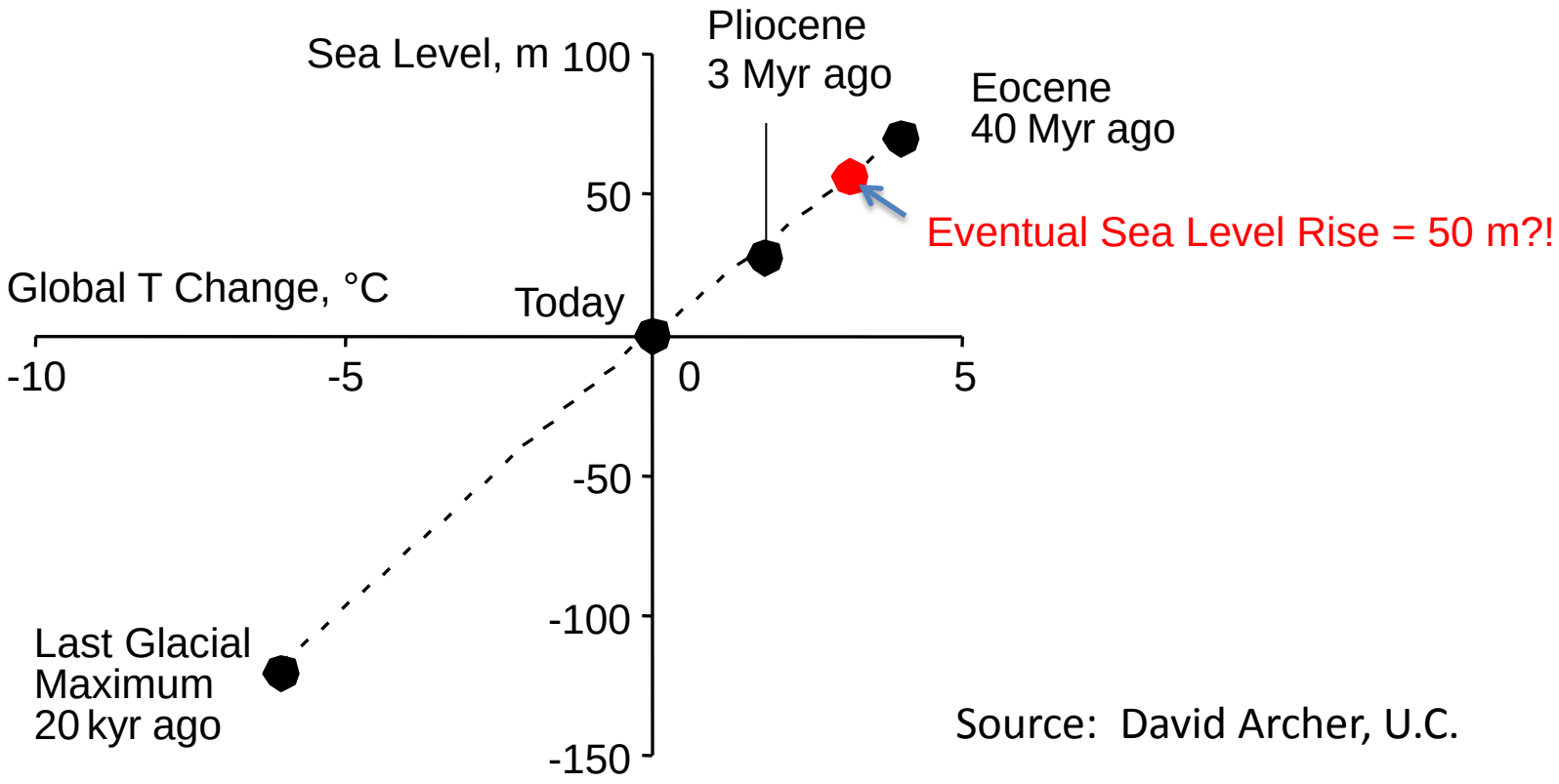


Re: Robert Rohde, U.C. Berkeley



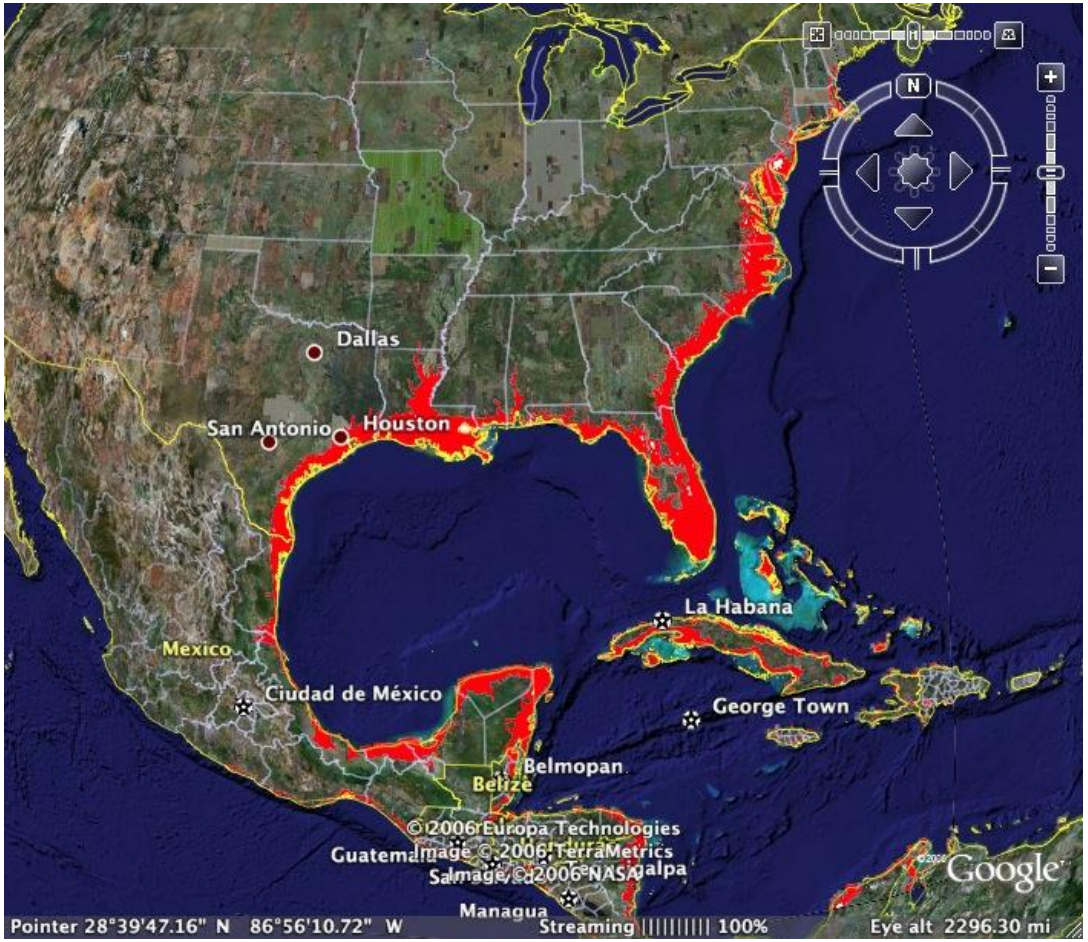
Rate = 2.5 meters/millennium, and accelerating.
Much of this rise currently is due to thermal expansion.

Simple Sea Level Extrapolation, Using Historical Data, Not Models



Source: David Archer, U.C.

20 meter Rise of Sea Level



Facing the Problem

The New York Times

The Opinion Pages

WORLD U.S. N.Y. / REGION BUSINESS TECHNOLOGY SCIENCE HEALTH SPORTS OPINION

OP-ED CONTRIBUTOR

Game Over for the Climate

By JAMES HANSEN
Published: May 9, 2012

(James Hansen is head of NASA Goddard Institute for Space Studies and is the world's leading climate modeller)

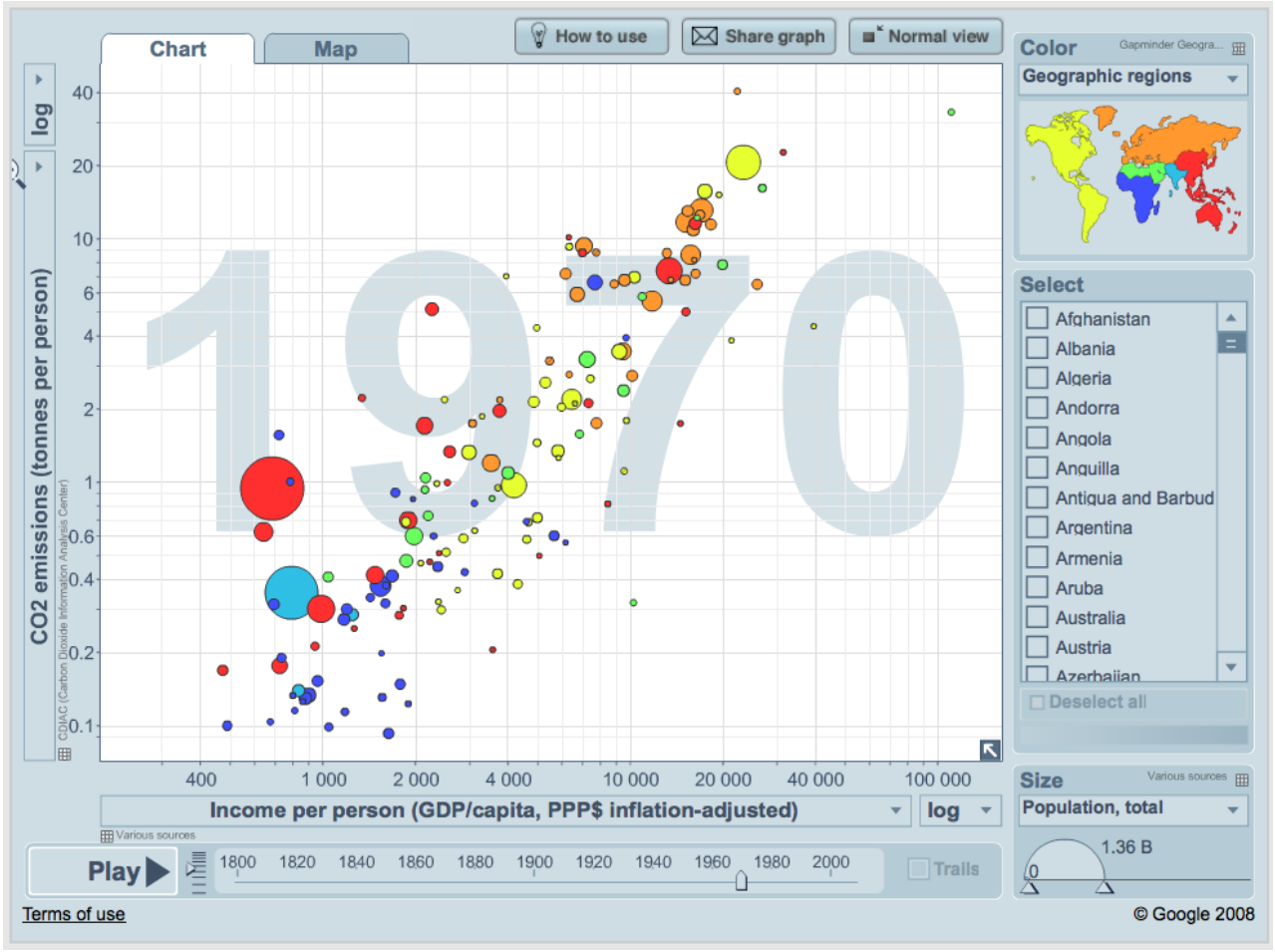
[If we continue on our present course…]

"Over the next several decades, the Western United States and the semi-arid region from North Dakota to Texas will develop semi-permanent drought, with rain, when it does come, occurring in extreme events with heavy flooding. Economic losses would be incalculable.

…

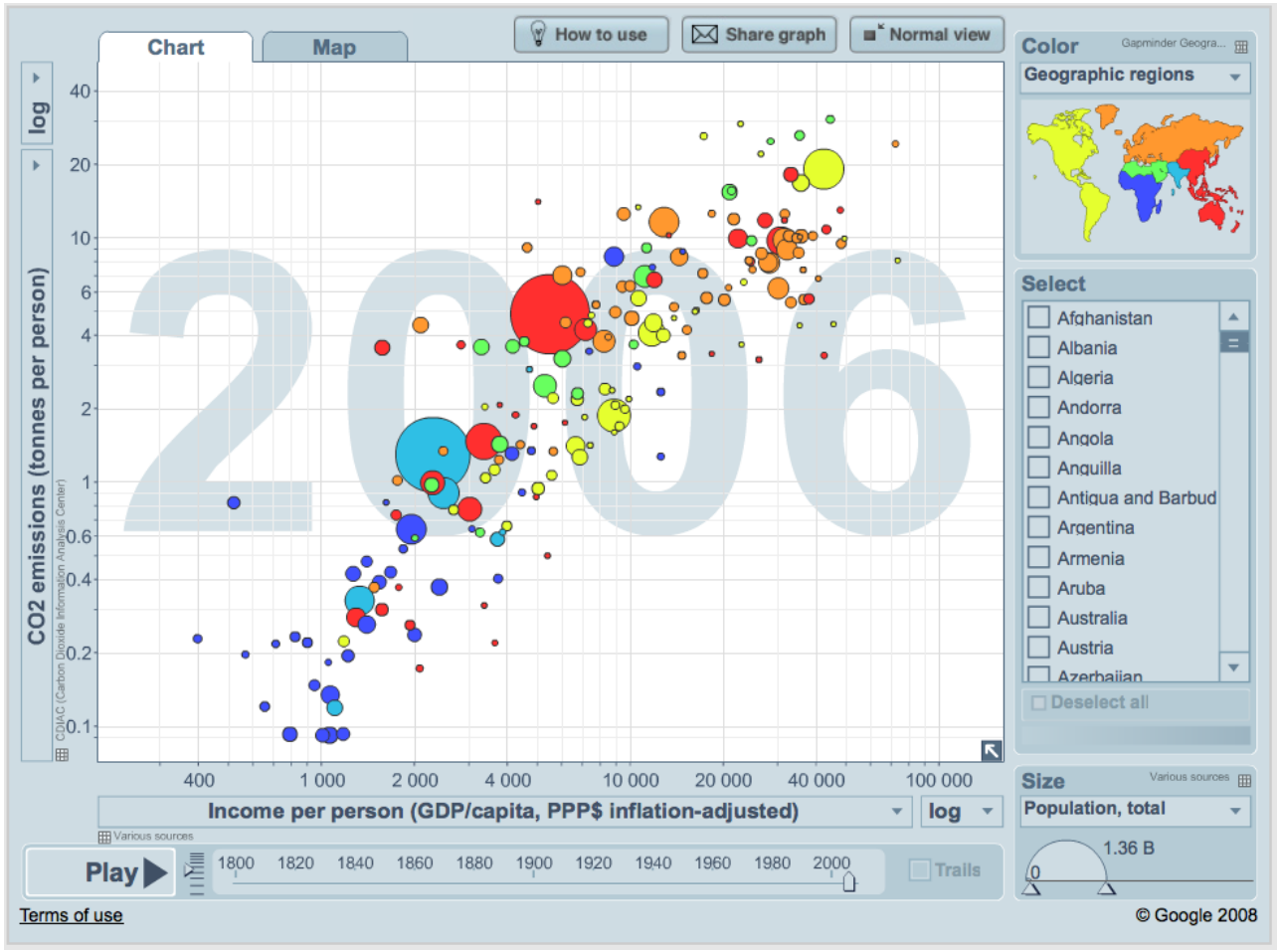
"Every major national science academy in the world has reported that global warming is real, caused mostly by humans, and requires urgent action. The cost of acting goes far higher the longer we wait — we can't wait any longer to avoid the worst and be judged immoral by coming generations."

The Economic Imperative for Burning Carbon



Gapminder.org

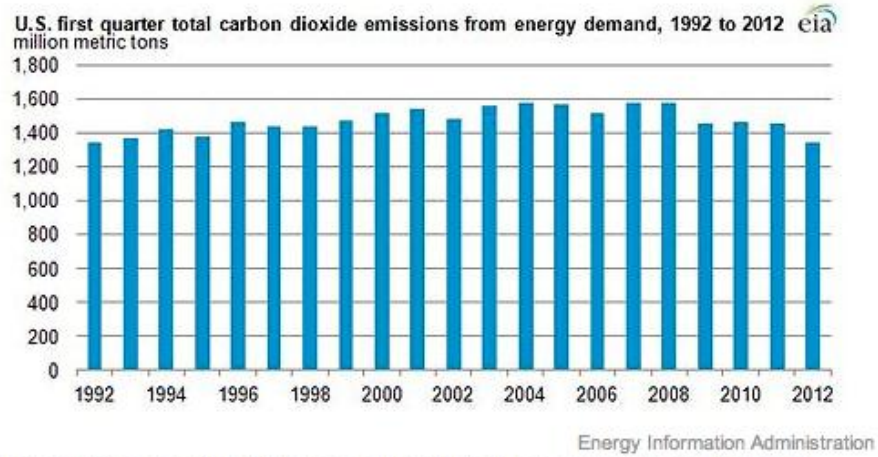
The Economic Imperative for Burning Carbon



Gapminder.org

A 20-Year Low in U.S. Carbon Emissions

By RACHEL NUWER



In the first three months of this year, energy-related carbon dioxide emissions were lower than in any first quarter in 20 years.

Business

Energy-related carbon dioxide emissions in the United States from January through March were the lowest of any recorded for the first quarter of the year since 1992, the federal Energy Information Administration reports.

The agency attributed the decline to a combination of three factors: a mild winter, reduced demand for gasoline and, most significant, a drop in coal-fired electricity generation because of historically low natural gas prices. Whether emissions will continue to drop or begin to rise again, however, remains to be seen, experts said Friday.

Natural Gas:	1100 lbs C/MWh
Oil:	1600 lbs C/MWh
Coal:	2200 lbs C/MWh

A Summary

- Climate on Earth is predictable
- One of the biggest 'knobs' that controls our climate is CO_2 in the atmosphere. Water vapor in the atmosphere follows the CO_2
- The Ice Ages give us a handle on exactly how sensitive the global temperature is with respect to changes in forcing (0.75^o for +1 Watt/m^2).
- The anthropogenic CO_2 emission from fossil fuels is a very significant forcing component and doubling the concentration of it in the atmosphere is predicted to lead to at least a 2.7^o C rise in temperature compared to pre-industrial times.
- The temperature sensor record is very clear that the global temperature has risen already about 1.5^o C. There have been no significant systematic errors brought to light in this measurement in some time.
- All major ice sheets are dramatically decreasing in mass. The complete melting of the summer Arctic polar ice cap will very likely occur within this decade.
- Predictions show severe consequences if we do not curtail our CO_2 emission.
- United States emissions of CO_2 have dropped in the last 20 years, so change is possible.
- Every physicist should be familiar with the details of global climate change and be able to confidently speak to the public about them.

Thank you for your attention!

If you are interested in talking about the solutions to anthropogenic global warming, please join the:

Fermilab Sustainable Energy Club !
Meeting tonight at 5:30 at User's Center